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Lentil Production in Germany Testing Different Mixed Cropping Systems, Sowing Dates and Weed Controls

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Abbreviations

A	Anicia
B	Barley
BL	Berglinse
Bw	Buckwheat
C	Cropping
CC	Companion Crop
CP	Crude Protein
HI	Harvest Index
HL	Hellerlinse
KH	Kleinhohenheim
L	Lentil
LAI	Leaf Area Index
LER	Land Equivalent Ratio
Ls	Linseed
M	Mulch
Mono	Monocropping
N	Nitrogen
Nt	Nitrogen Content
O	Oat
OLI	Oberer Lindenhof
R	Mixing Ratio
SEM	Standard Error of Mean
SL	Schwarze Linse
TCP	Total Crude Protein
TKW	Thousand Kernel Weight
W	Wheat
Y	Year

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CHAPTER 1

General Introduction

As well-known, legume crop plays an important role in agriculture. Lentils (*Lens culinaris* Medikus), a member of the legume family, were grown globally as seeds for human diet and straw for animal feed. Lentils were probably one of the oldest grain legume crops domesticated in the Old World (Sandhu and Singh, 2007). They are a cool season crop with a restricted root system which is only moderately resistant to high temperature and drought (Agriculture and Agri-Food Canada, 2010); therefore, they are mainly grown in the cooler temperate zones of the world or in the winter season in the areas, such as India and Australia, which have warm winter and hot summer (Yadav, 2007).

1.1 Importance of Lentils

1.1.1 Characteristics

Lentils are annual bushy herb plants with slender stems and many branches, erect, semi-erect or with a spreading growth habit (Sandhu and Singh, 2007). The plant height is in a range of 15 to 75 cm and there are 10 to 16 leaflets subtended on the rachis; upper leaves have simple tendrils while lower leaves are mucronate; all leaves are alternate, compound and pinnate (Muehlbauer *et al.*, 1985). Flowers are self-pollinating and flower stalks produce 1-3 flowers that develop pods. The length of pods is less than 2.5 cm and lentil pods normally contain one or two seeds (McVicar *et al.*, 2010).

There are many different types of lentils, concerning seed color, shape or size. The most common types used in cooking are brown, red and green lentils. Brown lentils are mild in flavor and the least expensive generally; red lentils have a slighter sweeter taste than brown ones and are better for soups and stews; green lentils are the finest and richest tasting but most expensive. Agriculture and Agri-Food Canada (2010) estimated that about 70% of world lentil production was the red type, 25% green type and 5% brown and other types. Canada and USA mainly produce the green type, whereas the rest of the world produces the red type lentils.

As a kind of legume crops, lentils contribute to the nitrogen input on the farm due to the biological nitrogen fixation. The nitrogen fixed by lentils may be used by the following crop or intercropped crops, which is important especially in organic farming. Prakash *et al.* (2002) reported that there was a 23.4% increase in rice yields following lentil compared to wheat in India. Based on the results from Campbell *et al.* (1992), they suggested that wheat grown in alternative years with grain lentils for 5 or 6 years could require a lower N-fertilizer recommendation than wheat grown in monoculture.

1.1.2 Nutritional Use

The lentil seeds are rich in protein content, carbohydrates and calories (Muehlbauer *et al.*, 1985). Its seeds are also a good source of several essential minerals, such as K, P, Fe, Zn, and vitamins B for the human nutrition (Bhatty, 1988). Lentil seeds are most commonly used as main dishes, side dishes or as sprouted grain in salads with rice or rotis (Sandhu and Singh, 2007). Its flour can be mixed with cereal crops for making breads and cakes (Williams and Singh, 1988). In some areas of Europe, Middle East, and India, lentil seeds have been used as a meat extender of substitute due to the high protein content and quality for a long time. Besides, it is reported by Williams *et al.* (1994) that lentils have the least concentrations of anti-nutritional factors, such as protease inhibitors and lectins which can cause flatulence. Lentil plant residues such as leaves, stems, husk and podwall left after threshing are also a good source of livestock feed.

1.1.3 Production and Trade

There are three major areas of lentil production in the world: North America, the Indian sub continent and Turkey (David *et al.*, 2007). Global lentil production reached a peak of 4.17 million tons in 2005. In 2009, global lentil production was 3.92 million tons, total acreage was 3.70 million ha and average yield was 1.06 ton ha^{-1}. Within about 50 countries where lentil is grown, Canada is now the biggest producer globally, with a production of 38.5% of world lentils; the second biggest producer is India (24.2%), followed by Turkey (7.7%) and USA (6.8%) (FAOSTAT, 2009). On average, about 66% of the lentils were consumed in the countries where they were produced. The major lentil-growing nations in the developed world (Canada, USA and Australia) grow lentils mostly to export to the developing world, especially to Asia, in where the main driver for increased demand and consumption of lentils is the increasing population (Erskine, 2009).

During the 2000s, global trade on lentils has been trending upwards from 1.14 million tons in 2001 to 1.32 million tons in 2008. The top three exporting countries were Canada, USA and Australia, covering 83% of the world exports in 2008. Import distribution was much wider than export, with the top ten importing countries accounting for 57% of imports. The main importing countries were Turkey, Sri Lanka, United Arab Emirates and Pakistan (FAOSTAT, 2008). Most of the lentils consumed in central Europe are imported from South Europe and North America. Germany imported considerable amounts of lentils to satisfy domestic demand every year, mainly from Canada and Turkey. Annual imported lentil of Germany was 25 kilotons on an average during 2001-2008, accounting for about 2% of total global imports (FAOSTAT, 2008).

1.1.4 Re-introduction of Lentils into German Organic Farming

In Europe, lentils remain a traditional and popular leguminous food (Horneburg, 2006). They had been widely grown in central Europe until the beginning of the 20th century; however, they had almost vanished from farming systems since the middle of the last century due to the neglected cultivation and research on this minor crop. Currently, more farmers renewed the interest to re-introduce lentils into German organic farming, as this crop has benefits in crop rotation due to its symbiotic N-fixation, and it increases crop biodiversity in arable land. Both aspects are relevant and desired in organic rotations, especially with regard to the future framework of European Common Agricultural Policy. Germany is one of the pioneering countries of organic farming. There has been a steady growth of organic farms in the past decades. In 2001, the German government introduced a set of measures to support organic farming (Willer and Yussefi, 2006), showing how important the role of organic farming is in German agriculture. Thus, there is a general need to increase lentil production in Germany to meet the high demands.

1.2 Lentil-based Cropping Systems

Lentils can be planted under mono and sequential cropping, intercropping, mixed cropping, relay cropping and multistorey cropping (Sekhon *et al.*, 2007). Many factors such as agro-climate, technology, socio-economy, planting and diet habits, determine greatly the success and adoption of any crop or cropping system in any area. In this study, the focus paid mainly on lentils in mixed cropping systems.

1.2.1 Lentil Monocropping and Sequential Cropping

Monocropping means a system in which the same crop is grown year by year in the same field. In the past, lentil monocropping was sustainable because of the low land pressure due to a small population. Nowadays, monoculture systems are considered risky to a certain extent because of unstable crop performance and yield achievement over different seasons, low returns and also the buildup of diseases and pests (Sekhon *et al.*, 2007). These problems may be effectively eased by reasonable crop rotations (sequential cropping). It was reported that sequential cropping was almost the only form of lentil cropping in Canada, Turkey, USA and Australia which together account for about 57% of global lentil production (FAOSTAT, 2009). In Canada, lentils were grown well in rotations with cereals such as durum wheat because they were suited to the same climate zones (Goodwin, 2003). As a shallow rooted crop, lentils did not use up the sub-soil moisture, thus wheat crop following lentils would have better yield and protein content (McVicar *et al.*, 2006). However, McVicar *et al.* (2006) also pointed that disease pressure would limit the rotation for lentils in where ascochyta blight (*Ascochyta rabiei* (Pass.) Lab.) was a problem. To reduce this risk, lentils should not be grown in the same field more frequent than one in three years. In South and West Asia like India, Pakistan and Nepal, lentil-rice rotation or lentil followed with maize, cotton, pearlmillet and sorghum were common cropping systems (Sekhon *et al.*, 2007).

1.2.2 Lentils in Mixed and Intercropping Systems

A system of growing two or more crops simultaneously without row arrangement on the same land is called mixed cropping, which is commonly applied in densely populated countries to provide more food. Mixed cropping systems in organic farming could supply a yield buffering capacity by different growing demands and periods of root, leaf and seed development of the plant varieties (Paulsen *et al.*, 2006). Intercropping refers to growing two or more dissimilar crops simultaneously on the same land with definite row arrangement. Mixed cropping or intercropping usually provides significant advantages in land use efficiency, crop productivity and monetary return compared with monoculture (Mandal *et al.*, 1990; Banik *et al.*, 2000; Akter *et al.*, 2004; Ciftci and Ülker, 2005). However, to select the suitable crop or variety and agronomic requirement aspect is very important. As a principle, the main crop and companion crops should have contrasting maturities to reduce competition for resources, different rooting characters in using soil moisture and nutrients from different depths and variable plant heights for better use of light (Sekhon *et al.*, 2007). In many years, cereal and legume, both for forage and for grain, are the most common intercrops or mixed crops. Wheat, barley, mustard and linseed are usually applied in lentil-based mixed/inter cropping systems in some countries or regions, such as in Bangladesh wheat (Akter *et al.*, 2004), in Central Europe barley (Schmidtke *et al.*, 2004), and in India mustard and linseed (Singh *et al.*, 2000; Sarkar *et al.*, 2004).

Some studies showed clearly that using proper mixtures in lentil-wheat mixed cropping systems obtained higher yield compared to monocropping, such as by Ahmed *et al.* (1987) who noted that in Bangladesh seeding ratios of 2:1 or 1:2 were the most compatible and profitable wheat-lentil mixed cropping systems. Ciftci and Ülker (2005) reported that lentil-wheat mixed cropping system at 80%:20% (lentil: wheat) or 70%:30% mixing ratios achieved high LER. Further, intercropping lentils with wheat could also alleviate some problems which occurred when growing lentils alone, such as the mixture reducing weed pressure (Liebman, 1988) and lowering the difficulty in mechanical harvestability due to lentils lodging habit (Cowell *et al.*, 1989). Similar as lentil-wheat mixed cropping, lentil-barley had also been tested as successful cropping over sole cropping in terms of productivity advantages (Mandal and Mahapatra, 1990; Ciftci and Ülker, 2005; Yağmur and Kaydan, 2006). The success of choosing mustard-lentil or linseed-lentil intercropping also depended on sowing arrangement; for example, single and double row lentil/mustard intercropping systems resulted in a 25% and 41% increase in LER, respectively (Rahman *et al.*, 2009); mustard-lentil intercropped at a 1:1 ratio resulted in maximum actual yield loss and intercropping advantage values (Banik *et al.*, 2000); lentil-linseed intercropping with 100%:25% ratio gave the same high intercrop lentil yield as sole lentil with additional linseed yield and had maximum net return, LER and benefit:cost ratio (Sarkar *et al.*, 2004).

1.3 Main Factors Affecting Lentil Grain Yield

1.3.1 Water

A lack of water - drought stress is one of the major yield limiting factors on lentils in many areas of the world (McWilliam, 1986; Muehlbauer *et al.*, 1995; Andrews and McKenzie, 2007), although this crop is usually adapted to grow in dryland cropping systems in semiarid area due to its lower water requirement than other legume crops (Carr *et al.*, 1995). It was reported that 80% of the variation in lentil grain yield in Mediterranean environment was due to the differences in seasonal rainfall (Erskine and EI Ashkar, 1993). Generally, lentils were grown on marginal lands that are relatively dry and without the benefit of irrigation (Muehlbauer *et al.*, 2006); however, if the rainfall is inadequate to let plants finish their life cycle, supplemental irrigation is necessary. Some authors (Yusuf *et al.*, 1979; McKenzie and Hill, 2004) showed several grain legumes including lentils had a critical period of sensitivity to water stress at flowering stage. The study from Shrestha *et al.* (2006a; 2006b) indicated that withholding water at lentil reproductive phases of flowering and podding had effects on both vegetative and reproductive growth, and different genotypes showed variations. In addition, lentils were greater drought tolerant than other temperate grain legumes such as pea or faba bean, probably due to the differences in their rooting depth and root proliferation (McKenzie and Hill, 2004). Lentils responded well to increased water supply. For example, a study (Hamdi *et al.*, 1992) found that two supplementary irrigations (50mm each) resulted in a 20% lentil yield increase per plant in Syria. The lentil yield is highly related to total seasonal rainfall amount in rainfed Mediterranean farming systems (Silim *et al.*, 1993).

1.3.2 Temperature

Besides drought stress, another major constraint on lentil yield is hot or low temperatures and the drought which is usually linked with hot temperatures (Muehlbauer *et al.*, 1995; Andrews and McKenzie, 2007). Hot or dry weather during lentil reproductive stages (flowering and pod filling) severely limited its productivity in many regions of the world (Erskine, 1985). It was generally accepted that heat affects dry matter distribution during reproductive period and that high temperatures have a negative effect on lentil seed yield (Muehlbauer *et al.*, 2006).

Sarker *et al.* (2003) reported that high May (pod-filling period) temperatures had a significantly negative correlation with lentil both grain and straw yield in Near East (Syria). In addition, Rhizobia were also vulnerable to high temperatures especially under moist conditions (Malhotra and Saxena, 1993).

As a cool season crop, lentils prefer to be grown as a cool weather or winter crop in the semi-arid tropical area. Compared with other temperate grain legumes, lentils were considered to be more tolerant of low temperatures, for instance, they had a better winter hardiness than pea or chickpea (Murray *et al.*, 1988). Although some lentils tested to be resistant to cool temperatures, they still need to be more tolerant of cold to ensure survival in some severe winters in countries such as Turkey, the USA and Canada. In the highlands of West Asia where lentils were normally spring-sown to reduce the high risk of low temperature damage, because these areas experienced overwinter temperatures of about -20 °C (Andrews and McKenzie, 2007). Currently, it was reported that some high yielding varieties had been released for use in the highlands (altitudes: 600 - 1400 m) of Turkey in where the temperature was -12 °C to -30 °C in winter (Sarker *et al.*, 2002, 2004). In addition, increasing the plant densities (~ 400 plants m^{-2}) could enhance the low temperature tolerance of lentils to some extent (Kusmenoglu and Aydin, 1995; Crook *et al.*, 1998).

Lentil yields could be optimized by matching crop growth and development with suitable temperatures and precipitation received during lentils growing season. This may be achieved by varying sowing time together with choosing an appropriate cultivar adapted to the region. Some studies reported that lentil grain yield increased significantly with early sowing, such as in the Mediterranean environments of northern Syria (Silim *et al.*, 1991) and in southern Australia (Siddique *et al.*, 1998). However, there was little current information on the adaptation and optimum sowing time of lentils to achieve the maximum yield under temperate climate conditions in Central Europe. Generally, early sowing can be expected to get higher yields because of the longer vegetative period for the dry matter accumulation which contributed to the grain yield. Nevertheless, early sowing may also increase the risk of diseases and crop lodging on lentils (Knights, 1987; Materne, 2003), and increase the number of weeds and weed biomass (Mishra *et al.*, 1996).

1.3.3 Weeds

Weeds are one of the most significant agronomic problems, especially on organic farms where herbicides are not allowed for weed control. It is well-known that weeds compete with crops for nutrients, water and light resources, thus reduce crop yield. Lentils are generally less competitive against weeds, due to their small and weak canopy (Chaudhary *et al.*, 2011) and slow growth rate during early season (Carr *et al.*, 1995). Thus, weeds are considered to be one of the most important factors affecting lentil yield. A study by Halila (1995) showed that the average yield loss on winter-sown lentils caused by weeds could be 60%-100%. While weed control applications significantly decreased the weed density and weed dry biomass and increased spring-sown lentil biomass and grain yield by 49% and 75%, compared with the unweeded treatment in eastern Turkey (Elkoca and Kantar, 2005).

Since chemical herbicides are absolutely prohibited in organic agriculture, developing non-chemical weed control alternatives is necessary. Generally, physical or mechanical control is common and a required method under organic status of production especially where labor cost is low. However, mechanical weed control is not suitable for lentils because of damage to the lentil shoots and roots due to its sensitivity (Stringi *et al.*, 1988) and twining architecture of the crop (Muehlbauer *et al.*, 1985). Inter-row weeding practices are only possible in situations where the crop is sown in rows wide enough for implements to pass (Brand *et al.*, 2007). An important and effective method for weed control in organic agriculture is to use intercropping or mixed cropping (Liebman and Dyck, 1993). As mentioned before, intercropping systems are more capable to use resources and control weeds than monocroping systems, for instance, the lentil-wheat intercropping (Carr *et al.*, 1995) and the pea-barley intercropping (Hauggaard-Nielsen, 2001).

Another option to reduce weeds could be using mulch. Mulching is a widely used alternative method for weed control in global agriculture (Gupta, 1991). Some studies reported that mulches could conserve the soil moisture, moderate the soil temperature and reduce weeds (Ashworth and Harrison, 1983; Birzins and Balatinecz, 1984; Powell *et al.*, 1987), thus making organic mulches popular in cropping systems. The typical organic mulch materials include wood, bark, or leaves singly or in combination (Duryea et al., 1999). Twigs and small stems which coming from periodic coppicing of hedgerows and pruning of trees, can be shredded and used for mulching. Gruber *et al.* (2008) showed that an application of 160 m^3 ha^{-1} woodchips mulch was significantly weed-suppressing in organic farming. The extent of weed suppressing on weed density and biomass varied with different woody species (Kamara *et al.*, 2000). However, previous studies of woodchip mulch focused mainly on trees in agroforestry systems or in orchards. There is limited information on the effect of woodchips in annual crops, especially on lentils.

1.4 Aim of the Study

The overall objective of this study was to design and improve lentil cropping systems under organic farming in Germany in terms of productivity and competitiveness performance, suitable species and proportion of companion crops, lentil cultivars, sowing dates, weed control, and seed quality. The results should be used to adapt lentil cropping systems to different local climatic conditions in Germany.

To achieve this goal, the specific objectives were:

- to optimize lentil-based mixed cropping systems through different combinations of companion crops and mixing ratios, which were expected to show different performance on crop productivity, weed infestation, and lentil lodging,
- to determine whether different sowing time (early, medium, late) have effects on a standard lentil-barley mixed cropping system in regard to crop yield and weed control,
- to test whether woodchip mulch can help suppressing weeds and increasing crop yield in lentil monocropping and mixed cropping systems,
- to determine whether different mixing ratios affect seed crude protein in lentil-cereals (barley, wheat) mixed cropping system.

1.5 Formal Structure of the Dissertation

The main part of this dissertation is based on four chapters containing manuscripts that have been published (Chapter 4) or submitted to peer reviewed journals (Chapter 2, 3, 5). Chapter 1 presents a general introduction which provides some basic information on lentil production and chapter 6 contains a general discussion.

CHAPTER 2

Optimizing Lentil-based Mixed Cropping with Different Companion Crops and Plant Densities in Terms of Crop Yield and Weed Control

The paper titled “Optimizing Lentil-based Mixed Cropping with Different Companion Crops and Plant Densities in Terms of Crop Yield and Weed Control” (Authors: L. Wang, S. Gruber & W. Claupein) was accepted by the journal *Organic Agriculture* (http://www.springer.com/life+sciences/agriculture/journal/13165).

The paper describes results from an experiment of lentil-based mixed cropping on an organic research station in Germany in order to identify the most suitable companion crop species and mixing ratio for lentils in terms of yield, weed infestation and lodging under temperate climatic conditions. This paper focuses on five different companion crops: barley, wheat, oat, linseed and buckwheat mixed cropped with lentils with five different sowing ratios. The study should help to open new options for growing organic lentils in temperate climate conditions and may guide the future of lentil production in multi-cropping.

Abstract

Mixed cropping of lentil (*Lens culinaris*) with five spring sown companion crops: naked-barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), oats (*Avena sativa*), linseed (*Linum usitatissimum*) and buckwheat (*Fagopyrum esculentum*) was compared with monocropping at the organic research station Kleinhohenheim, University of Hohenheim, Germany, in 2009 and 2010. Besides sole lentil and sole companion crops, three mixing ratios (3:1, 1:1, 1:3) were used. The aim of the study was to identify the most suitable companion crop and mixing ratio for lentils in terms of yield, weed infestation and lodging under temperate climatic conditions. Lentils yielded 1.47 t ha^{-1} in monocropping and 0.58-1.07 t ha^{-1} in mixed cropping, depending on the mixing ratio and companion crop. The land equivalent ratio (LER) was higher in mixed cropping than monocropping generally. Lentil-wheat and lentil-barley mixed cropping with a ratio of 3:1 resulted in the highest LER (ca. 1.50); lentil-linseed had the lowest LER for all ratios. Least lodging was observed in lentil-wheat and lentil-oat mixed cropping. Compared with lentil monocropping, mixed cropping with ratios of 3:1, 1:1 and 1:3 (lentil: companion crop) reduced weed biomass by 29%, 41% and 24%, respectively. Mixed cropping with wheat and barley for lentil in central Europe gives marked benefits in terms of grain yield, weed control and crop lodging resistance. Lentil production in organic farming systems is well suited to mixed cropping approaches.

Keywords: Intercropping; Land equivalent ratio; Monocropping; Lodging; Weed biomass

Abbreviations: B, barley; Bw, buckwheat; CC, companion crop; L, lentil; LAI, leaf area index; Ls, linseed; Mono, monocropping; O, oat; W, wheat.

Introduction

Lentils (*Lens culinaris* Medikus), legumes with high nutritional value, are grown mainly for human consumption on a global scale in semi-arid areas (Muehlbauer et al. 1995). At a global scale, lentil production was about 3.6 million metric tons in 2009 (FAO 2010), primarily in Canada, India and the United States. In Europe, lentils are a traditional and popular food

(Horneburg 2006). Most of the lentils consumed in central Europe are imported from southern Europe and North America. Recently, more and more farmers have realized the benefits of lentils and have begun to re-introduce this crop into German organic and conventional farming. In the past, lentils were commonly grown in mixed cropping systems in central Europe, but lentil cropping systems need to be developed that build on current technologies and practices.

The lentil plant has a weak stalk and is easily lodged. Lodged plants cannot be completely cut and picked up by combine harvesters, and result in yield loss, especially under the wet conditions that often occur in central Europe. The traditional cropping system for lentils in central Europe was therefore intercropping with cereals, mainly oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.) or rye (*Secale cereale* L.). These systems differ from the modern cropping systems in many semi-arid countries, which use monocropping (Brouwer et al. 2000; Sekhon et al. 2007). Many studies suggest that higher yields can be obtained from intercropping systems compared to monocropping (Akter et al. 2004; Ciftci and Ulker 2005; Mandal et al. 1990). However, yields of intercropped lentils depend on the competition with the companion crop. For example, lentils seem to be less competitive if intercropped with mustard (*Brassica juncea* L. Czern) than if intercropped with chickpea (*Cicer arietinum* L.) or barley (Gangasaran and Giri 1985). Intercropping can also offer advantages in weed control (Szumigalski and Rene 2005), especially in organic farming. Lentils grow slowly during early stages of plant development, making them generally poorly competitive against weeds (Muehlbauer et al. 1981). The combination of lentils and a companion crop in mixed cropping systems can reduce the weed pressure compared with monocropping (Carr et al. 1995). Therefore, suitable companion crops are needed for mixed cropping with lentils in Central Europe, and the optimum plant densities and mixing ratio should be investigated.

The share of organic farming has increased over the last twenty years and now occupies 4.3 % of the utilized agricultural area in Europe (EU-27), and 5.4 % of the utilized agricultural area in Germany in 2008 (EC 2010; BMELV 2011). Lentil mixed cropping provides an opportunity to introduce and establish a new crop for organic farming systems which provides nitrogen by fixation, and contributes to plant diversity at the field scale, especially in mixed cropping systems. The objective of this study was to design and improve lentil-based mixed cropping systems with reference to productivity and competitiveness with weeds, and to determine suitable species and proportions of companion crops for organic farming under temperate climate conditions.

Materials and Methods

Experimental site

A field experiment was carried out at the Kleinhohenheim organic research station (48° 43' N, 9° 11' E, and 435 m above sea level) of the University of Hohenheim, southwest Germany, in both 2009 and 2010. The research station is managed according to the organic standards of Bioland and Naturland, and has an 8-year crop rotation of grass/clover (two years), winter wheat (*T. aestivum*), oats (*A. sativa*), faba bean (*Vicia faba* L.), spelt (*Triticum spelta* L.), maize (*Zea mays* L.)/potatoes (*Solanum tuberosum* L.), and triticale (× *Triticosecale* Wittm. ex A. Camus.). In each year the experiment with lentils was integrated within the faba bean field. The long-term (1991-2010) annual average rainfall and air temperature are 728 mm and 9.9 °C, respectively. Total rainfall and mean temperature during the lentil growing season from April to August was 601 mm and 16.3 °C in 2009, 362 mm and 15.4 °C in 2010 (Fig.1). The dominant soil types are Luvisols and Cambisols, with loess to sandy loamy clay textures. The landscape is hilly. In 2008, the baseline topsoil (0-20 cm) characteristics were: pH 7.0, P_2O_5 24 mg/100 g soil, K_2O 19 mg/100 g soil, MgO 10 mg/100 g soil. Soil mineral nitrogen (N_{min}, nitrate and ammonium fractions) was determined in both 0-30 cm and 30-60 cm soil layers before sowing and was 9 kg ha^{-1} in both layers in 2009, with 8, and 6 kg ha^{-1} in 2010.

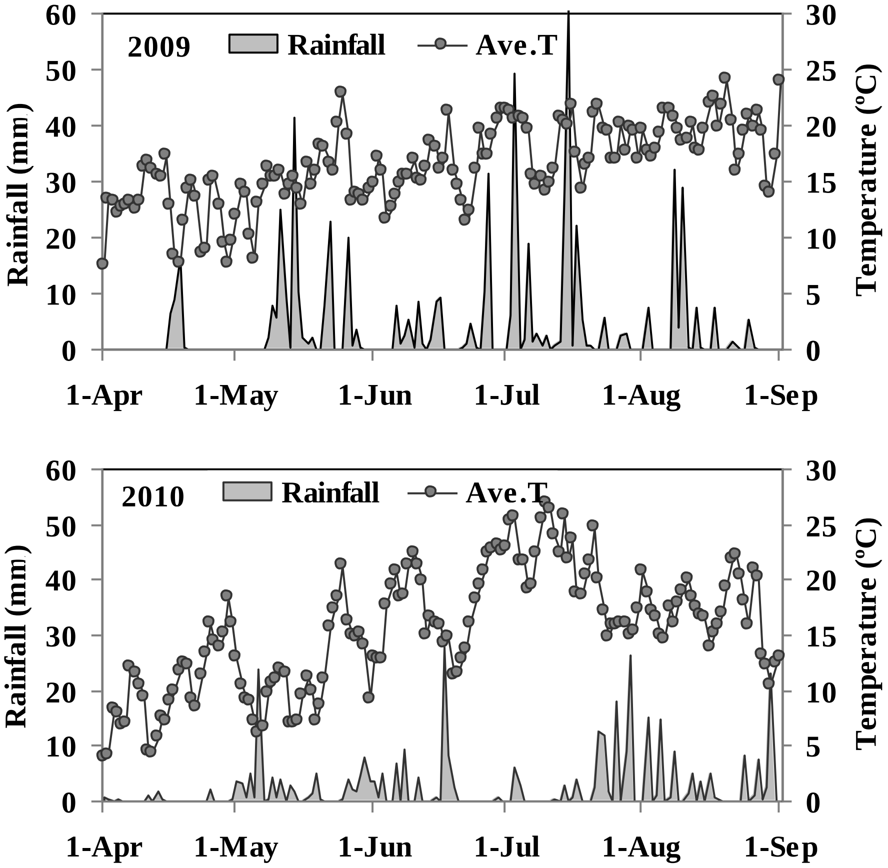

Fig. 1 Total rainfall (mm) and average temperature (°C) during the lentil growing season (from April to August) in 2009 and 2010 at Kleinhohenheim, Germany

Experimental design and data collection

Lentil (cv. Anicia; green marbled lentil) was cropped in mixtures with five spring-sown companion crops: naked-barley (cv. Hora), wheat (cv. Triso), oats (cv. Dominik), linseed (*Linum usitatissimum* L., cv. Scorpion), and buckwheat (*Fagopyrum esculentum* Moench, cv. Spacinska). Total target crop density for all systems was 240 plants m^{-2}. Lentil (L) and companion crop (CC) were grown both as monocrops and in mixed cropping systems with different proportions (3:1, 1:1, and 1:3 of L:CC), referring to the total seed density. A Graeco-Latin Square design with three replicates was chosen for the experiment. This allows the correction for potential row and column effects and ensures that all treatments are distributed equally in the field. As lentil monocropping (4:0) was included for each cropping system in the Graeco-Latin Square design, the total number of plots was 75 (5×5×3). Individual plots consisted of 16 rows spaced 15 cm apart, with a length of 4.2 m. Crops were sown using a plot drill at a uniform sowing depth of 3 cm on 23 April (2009) and 20 April (2010). Leaf area index (LAI) of crops in each plot was measured using LAI-2000 measurement on 12 July in the second year (lentil early pod filling stage). Crop lodging was recorded at late maturity stage (9 August 2009 and 7 August 2010). Crop lodging of lentil and companion crops was recorded on a 1-9 rating scale, where 1 indicates main stem strictly erect and 9 means totally lodged. This is the German and European standard rating method which is usually used by breeders and agronomists, and which is for instance described by the Bundessortenamt (German Federal Office for Plant Varieties, www. bundessortenamt.de).

A sample area of 1 m^2 (2 × 0.5 m^2) per plot was harvested by hand-pulling of all crops and weeds on 18-21 August (2009) and 16-20 August (2010) when the majority of lentil pods had turned brown and some had just begun to open. Separation of lentils, companion crops and weeds was performed by hand and then the roots of all crops and weeds were cut by scissors and discarded. Grain yield, above ground biomass, and weed biomass were determined on a dry weight basis. All samples were oven-dried for three days at 80°C to a constant weight. Dry samples of each plot were threshed using a small pedestal threshing machine at a speed of 550 rpm for lentils and 750~850 rpm for companion crops.

The “land equivalent ratio” is used as an index of biological advantage, which is defined as the relative land area that would be required for sole crops to produce the same yield achieved in intercropping (Willey 1979). An LER value higher than 1.0 indicates an advantage in favor of intercropping, whereas a value lower than 1.0 means a disadvantage. Land equivalent ratio (LER) was therefore calculated to compare the relative advantage of mixed cropping to monoculture using the formula of Willey (1979):

$$LER = (LER_a + LER_b) = \left(\frac{Y_{ab}}{Y_{aa}} + \frac{Y_{ba}}{Y_{bb}} \right)$$

where LER_a and LER_b are the partial LER of crop A (lentil) and crop B (companion crop), respectively.

Y_{aa} and Y_{bb} represent the pure stand yields of crop A (lentil) and crop B (companion crop) in monocropping.

Y_{ab} means the mixture yield of crop A (lentil) in combination with B (companion crop), and;

Y_{ba} means the mixture yield of crop B (companion crop) in combination with A (lentil).

Statistical analysis

Analysis of variance was performed using the MIXED procedure of SAS version 9.2 (SAS Institute 2009). The model in the syntax of Patterson (1997) is given by:

C + R + C · R + Y + Re · Y : C · Y + R · Y + C · R · Y + Row · Re · Y + Column · Re · Y

where C, R, Y, Re denote cropping system, mixing ratio, year and replicate; Row and Column mean block effect in row and column, respectively. Fixed effects are given before the colon, random effects after the colon and interactions are denoted by a dot between the corresponding main effects. Data were log transformed to get a normal distribution and homogeneity of variance, if necessary. For letter description, a multiple *t*-test was made only when the *F*-test was significant.

Results

Crop Yield

Cropping system and mixing ratio had significant effects on lentil grain yield. There were no significant interactions between cropping system and mixing ratio (Table 1). Lentil grain yield averaged across all mixing ratios ranged from 0.72 to 0.96 t ha^{-1} among the five companion crops, with the highest yield in the lentil-buckwheat (LBw) mixed cropping. Averaged over two years, lentil grain yield from monocropping was 1.47 t ha^{-1}; in the mixtures, yield depended on the mixing ratio and ranged from 1.07 t ha^{-1} (ratio lentil: companion crop 3:1) to 0.58 t ha^{-1} (ratio 1:3) across all crops. The grain yield and biomass of lentils declined significantly as the mixing ratio of lentils decreased. Lentil yield in mixed cropping with three mixing ratios (3:1, 1:1, and 1:3 of L: CC) was reduced by 27%-61% compared with lentil monocropping. The decline in biomass was higher than that of grain yield, which resulted in a significant increase of the lentil harvest index (HI) as grain yield decreased. There was a significant difference of experimental year on lentil grain yield and biomass. Overall averaged, lentil yield was 1.41 t ha^{-1} in 2009 and 0.71 t ha^{-1} in 2010 due to weather variation (data not shown).

Table 1 Lentil grain yield (t ha^{-1}), aboveground dry biomass (t ha^{-1}) and harvest index (HI) of lentil-barley (LB), lentil-wheat (LW), lentil-oat (LO), lentil-linseed (LLs) and lentil-buckwheat (LBw) mixed cropping systems in different mixing ratios (lentil: companion crop) over two years (2009-2010, mean values). No significant differences for values followed by the same letters in each column within the cropping system or mixing ratio, P<0.05. SEM, standard error of mean

	Grain yield	SEM	Biomass	SEM	HI	SEM
Cropping system (C)						
LB	0.74 b	0.04	1.66 a	0.12	0.46 a	0.02
LW	0.78 b	0.04	1.76 a	0.13	0.44 a	0.02
LO	0.72 b	0.03	1.58 a	0.12	0.46 a	0.02
LLs	0.85 ab	0.04	1.89 a	0.14	0.44 a	0.02
LBw	0.96 a	0.05	2.05 a	0.15	0.46 a	0.02
Mixing ratio (R)						
4:0	1.47 a	0.07	3.63 a	0.30	0.41 b	0.02
3:1	1.07 b	0.03	2.50 b	0.11	0.42 b	0.01
1:1	0.85 c	0.03	2.00 c	0.08	0.43 b	0.01
1:3	0.58 d	0.02	1.13 d	0.05	0.50 a	0.01
Source of variation	*P* values		*P* values		*P* values	
C	0.0456		0.2356		0.8986	
R	0.0119		<0.0001		<0.0001	
C×R	0.6881		0.9365		0.4829	
Year	<0.0001		<0.0001		0.4423	

Companion crop grain yields and biomass generally decreased as their mixing ratio decreased. There were significant differences in yields and biomass due to companion crop species, mixing ratios, species × mixing ratio interaction, and experimental years (Table 2). The increase of barley yield in a mixture (relative to sole cropping) along with an increasing share of barley in the mixture was 71%, 80% and 87%, corresponding to lentil: barley in 3:1, 1:1 and 3:1 ratios. Similar effects were observed for wheat (63% – 72% – 91%) and oats (49% – 70% – 90%). Unlike these three cereal crops, linseed (23% – 47% – 68%) and buckwheat (31% –53% – 78%) grain yields were similar to their target mixing ratios.

Table 2 Companion crop grain yield and aboveground dry biomass of lentil-barley (LB), lentil-wheat (LW), lentil-oat (LO), lentil-linseed (LLs) and lentil-buckwheat (LBw) mixed cropping systems in different mixing ratios (lentil: companion crop) over two years (2009-2010, mean values). Lower case letters mark significant differences within the same cropping system in a row, and upper case letters those between cropping systems in a column, P<0.05. SEM, standard error of mean

	Mixing ratio							
System	3:1	SEM	1:1	SEM	1:3	SEM	0:4	SEM
	Grain yield (t ha^{-1})							
LB	1.12 b B	0.13	1.25 ab B	0.15	1.37 ab B	0.16	1.57 a B	0.19
LW	2.07 c A	0.24	2.35 bc A	0.28	2.98 ab A	0.35	3.28 a A	0.39
LO	1.68 c A	0.20	2.39 b A	0.28	3.09 a A	0.36	3.44 a A	0.41
LLs	0.42 d D	0.05	0.87 c B	0.10	1.26 b B	0.15	1.85 a B	0.22
LBw	0.62 d C	0.07	1.04 c B	0.12	1.54 b B	0.18	1.98 a B	0.23
	Biomass (t ha^{-1})							
LB	2.99 b B	0.37	3.09 ab B	0.38	3.23 ab B	0.40	3.87 a C	0.47
LW	4.60 c A	0.56	5.26 bc A	0.64	6.46 ab A	0.79	7.30 a AB	0.90
LO	4.44 c A	0.54	5.81 b A	0.71	6.95 ab A	0.85	7.48 a A	0.92
LLs	1.36 d C	0.17	2.58 c B	0.32	3.63 b B	0.44	4.97 a BC	0.61
LBw	1.81 d C	0.22	2.91 c B	0.36	3.89 b B	0.48	4.98 a BC	0.61

	P values	
Source	Grain yield	Biomass
C	0.0046	0.0147
R	<0.0001	0.0084
C×R	0.0008	0.0003
Year	0.0091	0.0428

Almost all mixed cropping systems showed a land equivalent ratio (LER) greater than 1.0, except for the lentil-linseed (LLs) cropping system with a ratio of 3:1 (lentil: linseed) (Table 3). There was a significant effect of the companion crop on the LER. On average, lentil mixed cropping was superior to monocropping by 5% - 40%. The lentil-barley (LB) and lentil-wheat (LW) cropping systems at 3:1 (L: CC) mixing ratio recorded higher LER (ca. 1.50) compared with other combinations.

Table 3 Land equivalent ratio (LER) of lentil-barley (LB), lentil-wheat (LW), lentil-oat (LO), lentil-linseed (LLs) and lentil-buckwheat (LBw) mixed cropping systems in different mixing ratios (lentil: companion crop) over two years (2009-2010, mean values). No significant differences for values followed by the same letters in the column, $P<0.05$. SEM, standard error of mean

	Mixing ratio (R)				
Cropping system (C)	3:1	1:1	1:3	Mean	SEM
LB	1.51	1.37	1.28	1.38 a	0.05
LW	1.46	1.36	1.37	1.40 a	0.05
LO	1.18	1.23	1.29	1.23 a	0.05
LLs	0.98	1.11	1.06	1.05 b	0.04
LBw	1.17	1.29	1.29	1.25 a	0.05
Mean	1.24	1.27	1.25		
Source of variation	LER (*P* values)				
C	0.0262				
R	0.8249				
C×R	0.0840				
Year	0.8265				

Crop LAI and weed biomass

Mixing ratios affected crop LAI significantly whereas cropping systems and cropping system × mixing ratio interactions did not have a significant effect on crop LAI. Crop LAI was significantly higher in lentil monocropping and mixed cropping at all three ratios than that in companion crop monocropping; however, there were no significant differences among the four ratios of lentil (Fig. 2). The LAI of lentil monocropping was around 3.8 and the LAI ranged from 2.9 to 4.6 in lentil three mixtures. The LAI of all the companion crops was not more than 3.0. Generally, adding companion crops in lentil-cereal (lentil-barley, lentil-wheat, and lentil-oat) mixed cropping with high mixing ratios (3:1 and 1:1) increased the LAI of the mixture.

Weed biomass was significantly different between the cropping systems, and there was also a significant interaction between cropping system and mixing ratio (Fig. 3). Mixed cropping of lentils with oat in lentil-oat (LO) cropping system suppressed weeds most significantly. The total weed biomass in this mixture was 15-30 g m^{-2} (depending on the mixing ratio), followed by lentil-wheat (33-48 g m^{-2}) and lentil-barley (48-74 g m^{-2}) mixed cropping; the weed biomass in lentil-linseed and lentil-buckwheat mixed cropping were higher, with 63-140 g m^{-2} (LLs) and 60-142 g m^{-2} (LBw). Mixed cropping of lentils with different companion crops in ratios of 3:1, 1:1 and 1:3 (L:CC) reduced the weed biomass by 29%, 41% and 24% in the mean of two years and across all companion crops.

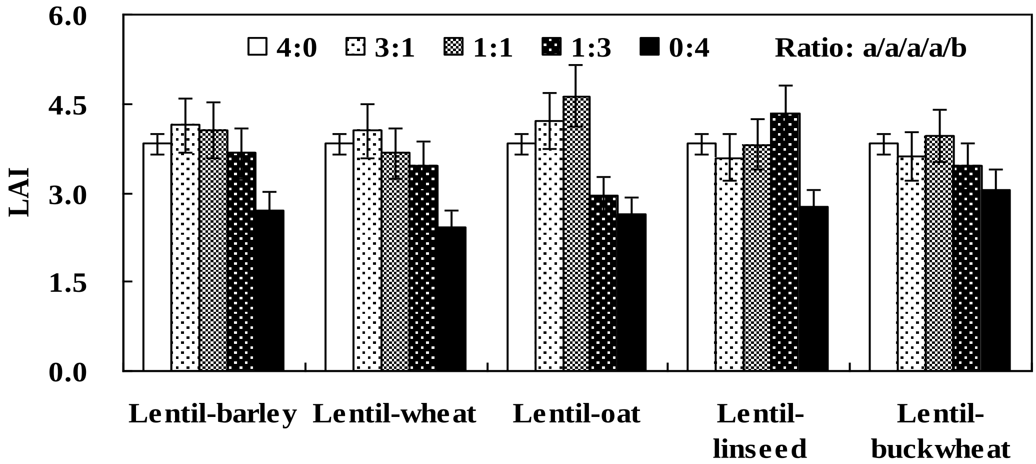

Fig. 2 Leaf area index (LAI) in lentil-barley (LB), lentil-wheat (LW), lentil-oat (LO), lentil-linseed (LLs), and lentil-buckwheat (LBw) mixed cropping systems with different mixing ratios (lentil: companion crop, 4:0 - 0:4). No significant differences for values followed by the same letters, P<0.05. All values are means, ±S.E. (bars)

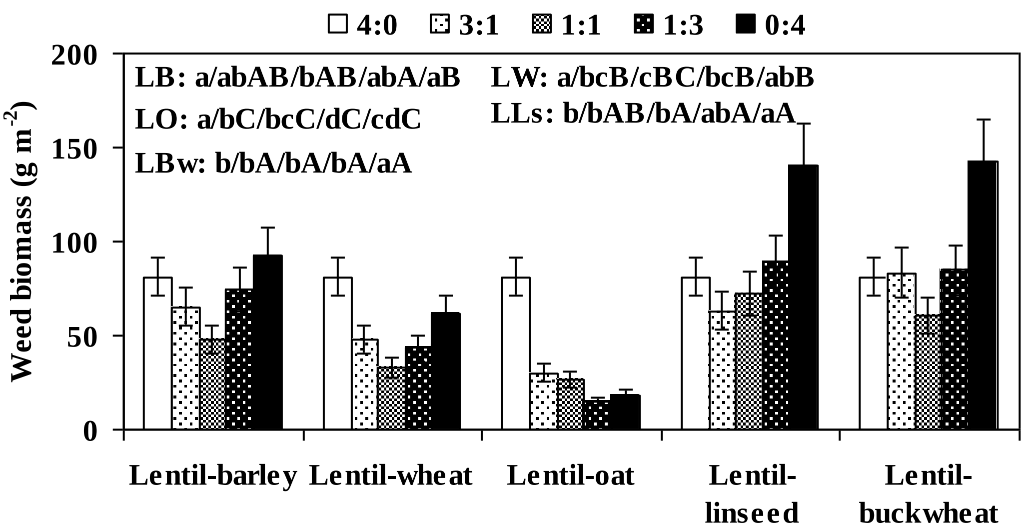

Fig. 3 Weed dry biomass (two years mean) in lentil-barley (LB), lentil-wheat (LW), lentil-oat (LO), lentil-linseed (LLs), and lentil-buckwheat (LBw) mixed cropping systems with different mixing ratios (lentil: companion crop, 4:0 - 0:4). Lower case letters mark significant differences within the same cropping system, and upper case letters those between cropping systems, P<0.05. All values are means, ±S.E. (bars)

Crop lodging

Lodging of lentils ranged from nearly full lodging in monocropping to slight lodging (ca. 2) in mixed cropping (Fig. 4). A decreasing proportion of lentils in the mixture usually decreased the risk of lodging for both lentil and companion crops significantly. Only the companion crops wheat and oat were not affected by the number of admixed lentil plants in terms of lodging. Wheat and oat were also able to a certain extent to prevent lentils from severe lodging in mixtures with high proportion of lentils (3:1 mixtures).

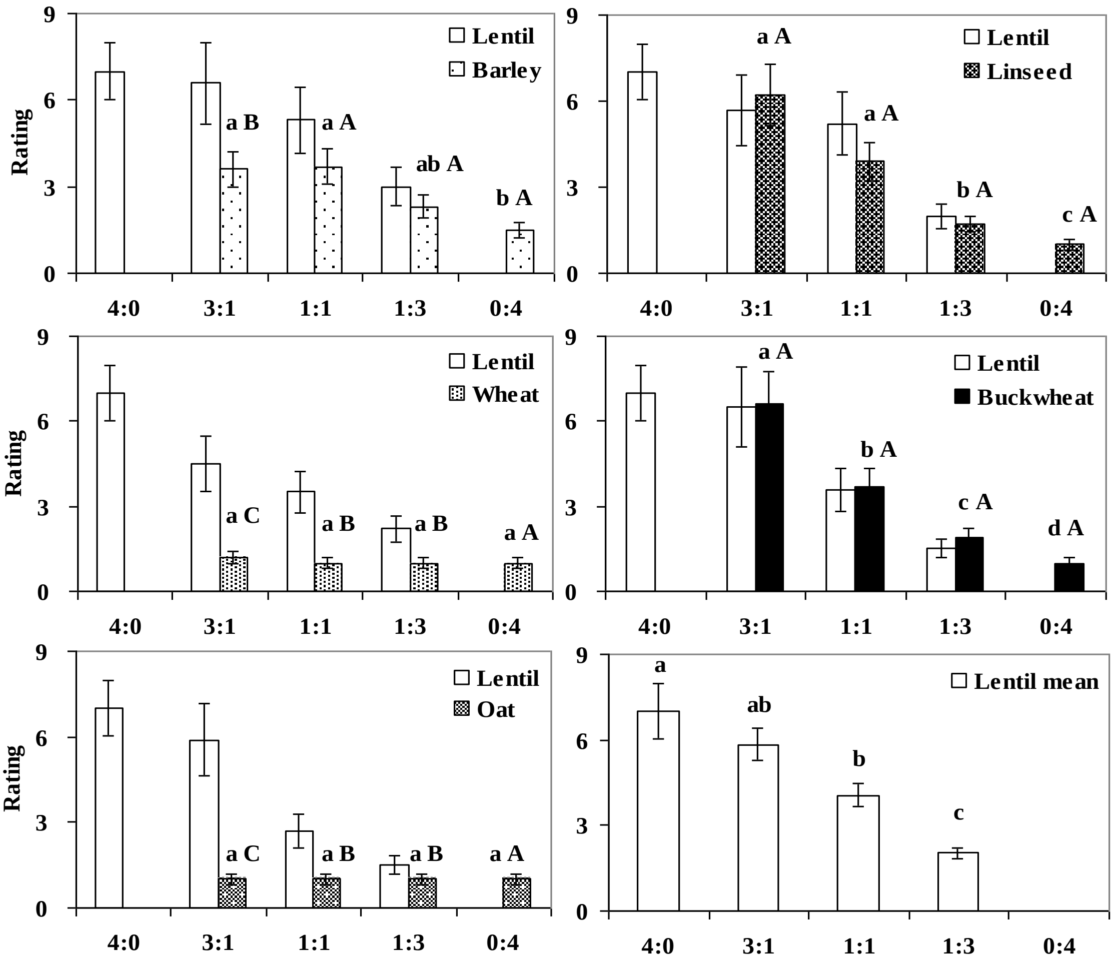

Fig. 4 Lodging rating of lentil and companion crops in lentil-based mixed cropping systems with different mixing ratios (lentil: companion crop, 4:0 - 0:4) at lentil maturity (two years mean). 1: no lodging, 9: full lodging. Lower case letters mark significant differences within the same cropping system, and upper case letters those between cropping systems, $P<0.05$. All values are means, ±S.E. (bars)

Discussion

The mean grain yield of our study was higher (1.47 t ha^{-1}) than that reported from practical commercial farming in southwest Germany (absolutely < 1 t ha^{-1}, Mammel W, personal communication). This difference was probably a result of the harvesting method in the current study which was uprooting of the total plants by hand. All in all, the lentil yield obtained from the experiment were slightly lower than usual yields under semi-arid conditions which range from 0.56 to 1.38 t ha^{-1} (Greece, organic farming; Vlachostergios et al. 2011), 1.0 t ha^{-1} to 2.5 t ha^{-1} (Australia, conventional farming; Siddique et al. 1998), about 1.2 t ha^{-1} (Turkey, dryland conventional farming; Yagmur and Kaydan 2006), and 1.48 t ha^{-1} (Saskatchewan, Canada; McVicar et al. 2010).

The increase of cereals (barley, wheat and oat) yield (%) in a mixture (relative to sole cropping) exceeded the sown mixing ratio, probably because the cereals produced more effective tillers at low sowing densities and under low interspecific competition from the lentils. Cereals have high capacity for competition with lentils. Cereal crops, with relatively higher growth rates, greater height and more extensive root systems, could be favored when they are associated with legumes (Ofori and Stern 1987). In a mixture of lentils and wheat in the ratio 1:1 (Patrick et al. 1995), the lentil yield declined by 70% to 90% because lentils were unable to compete with wheat for light and possibly other growth resources. Buckwheat and linseed seemed to have similar interspecific competition ability with the lentils thus buckwheat and linseed could not utilize the higher spacing in the standing crop by outcompeting the lentils. The competition ability of lentils also depends on the climate. As shown by Ahlawat et al. (1985), lentils mixed cropped with wheat seemed to be more competitive in sub-humid than in semi-arid environments. In the current study, mixed cropping resulted in a slightly lower relative lentil yield than its initial mixing ratio. However, the total grain yield (lentils plus companion crop) was higher than lentil or companion crop monocropping.

Almost all combinations in this study showed superior land efficiency of mixed cropping versus monocropping (Table 3). Especially the barley and wheat at a mixing ratio of 3:1 resulted in a high LER of ca. 1.50 and demonstrated a potential yield advantage of lentil mixed cropping compared to monocropping. Similar results were found by Akter et al. (2004), Ciftci and Ulker (2005) with the maximum LER of 1.52 and 1.15 respectively. A slight over-estimation of the LER for cereals can be assumed because the sowing densities of barley, wheat and oat monocropping were lower than usual for that location due to the experimental design.

The weed suppression of the mixtures were similar to studies of Carr et al. (1995) for lentil-wheat mixed cropping, Banik et al. (2006) for wheat-chickpea intercrop and Agegnehu et al. (2006) for barley-faba bean mixed cropping, who all found weed infestation to be significantly lower in mixed cropping than in monocropping. Mixed cropping can be very efficient in terms of weed control (Hauggaard-Nielsen et al. 2001; Liebman and Dyck 1993; Olasantan et al. 1994). In this study, the LAI was higher in certain mixtures which allowed less light to penetrate the canopy to the soil, and thus the weeds would be suppressed. This suggested that mixed cropping can be a practical method for weed management in organic lentil production.

Lodging causes yield loss because seeds close to the ground cannot be harvested by a combine harvester, and a loss in quality because of the risk of higher grain moisture, pre-harvest sprouting and infection with fungi. The lentil cultivar Anicia which was used in the current experiment appeared to benefit from the companion crop to avoid lodging. Other lentil cultivars with lower risk of lodging might be grown in monocropping to achieve higher yields. Linseed turned out to be especially unsuitable for mixed cropping with lentils because its slim stem also lodged easily. Additionally, the fiber in the linseed stems caused serious harvest problems. Although the LER benefits were not so high, buckwheat together with lentils seems to be a crop that fits well in organic farming because buckwheat belongs to a different genus than other crops, and may help to break infection cycles of pest and diseases, for instance, buckwheat as living mulch was shown to be useful tools in controlling multiple pest complexes in zucchini (Hooks et al. 1998). Additionally, the flowers of buckwheat attract beneficial insects and thus provide a source for biodiversity for the whole farm area.

Conclusions

Mixed cropping of lentil is a cropping system that provides significant advantages in yield and weed control, and therefore seems promising for organic farming under temperate climates. Except for linseed, all tested species can be used as companion crops. Mixed cropping with wheat and barley for lentil in central Europe gives marked benefits in terms of grain yield, weed control and crop lodging resistance. Lentil production in organic farming systems is well suited to mixed cropping approaches. Developing an appropriate mixing ratio will require further consideration of the total yield (LER), the risk of crop lodging, and marketing considerations of both lentils and the corresponding companion crop.

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Introduction to Chapter 3

In the previous chapter 2, it was shown clearly that different lentil-based mixed cropping systems had significant advantages in yield productivity and weed control compared to lentil monocropping. Furthermore, lentils need a companion crop to help resisting crop lodging. By testing these five companion crops, it was found out that most of them (except for the linseed) were suitable to mix-cropped with lentils, especially for **the cereals** (barley and wheat).

Lentil-barley cropping system is a local and traditional cropping system in the study area. Results from the paper 1 confirmed the superiority of this cropping system; however, currently there is little information about the cultivation such as the optimum sowing date. To explore the potential growth period for lentils to better adapt the cropping system to the temperate climate in Central Europe this was surveyed in the next paper.

CHAPTER 3

Effect of Sowing Dates on Yield and Weeds in A Lentil-barley Mixed Cropping System

The paper titled “Effect of sowing dates on yield and weeds in a lentil-barley mixed cropping system” (Authors: L. Wang, S. Gruber & W. Claupein) was submitted to the *Journal of Agricultural Science* in January 2012, the current process of the paper is under review (http://journals.cambridge.org/action/displayJournal?jid=AGS).

The paper describes results from a 2-year field experiment of a standard lentil-barley mixed cropping system at two sites (an organic research station and a conventional research station) in Germany. The aim of this study was to examine the adaptation of lentils to the temperate climate conditions of Central Europe in order to determine the effect of sowing time on crop yield and weed control. Four different genotypes of lentil mixed cropped with one cultivar of spring naked barley at three sowing dates (early, medium, and late) were studied in this paper.

The clear results of the study open new perspectives for growing lentils in Central Europe from where the crop has vanished over the last decades.

Summary

The study examined variation in sowing dates on lentils (*Lens culinaris*) in a standard lentil-barley (*Hordeum vulgare*) mixed cropping system in the temperate climate of central Europe to determine effects on crop yield and weed control. A 2-year (2009-2010) field experiment was carried out at the organic research station Kleinhohenheim (KH) and at the conventional research station Oberer Lindenhof (OLI) of the University Hohenheim, SW Germany. The crop was sown at three dates in the period from March to May. Grain yield was significantly higher at the earliest sowing both for lentils (3.0 t ha^{-1} at KH, 2.4 t ha^{-1} at OLI) and barley (1.2 t ha^{-1} at KH, 2.6 t ha^{-1} at OLI). Lentil seed number $plant^{-1}$, barley seed number ear^{-1}, and crops' thousand kernel weight decreased significantly with delayed sowing. Weed biomass at KH increased significantly with delayed sowing and was independent of the lentil genotype, whereas sowing date had no significant effect on overall weed biomass production at OLI. Unlike weed biomass, weed density generally decreased significantly with delayed sowing. The results indicate that early sowing can increase the yield of lentils, and can be used as an indirect method of weed control in organic farming.

Keywords: Competition; Lentil; Sowing date; Weed; Yield

Introduction

Lentils (*Lens culinaris* Medik.) have high nutritional value and are grown on a global scale mainly for human consumption (Muehlbauer *et al.*, 1995). The crop has benefits in crop rotation due to its symbiotic N-fixation, and it increases crop biodiversity in arable land. Both aspects are relevant and desired in organic and conventional rotations, especially with regard to the future framework of European Common Agricultural Policy.

In Europe, lentils are considered one of the important leguminous food crops, following pea and *Phaseolus* bean (Horneburg, 2006). As both cultivation and scientific research on lentils were neglected in Germany and Central Europe in general for several decades, lentils have almost vanished from this region over the past 50 years, although they remain a well-known and popular food. Most of the lentils consumed in Central Europe are imported from South Europe and North America. On a global scale, lentil production was about 3.6 million metric tons in 2009 (FAO, 2010), produced mainly by Canada, India, the United

States and Turkey.

Recently, farmers have begun to realize the value of lentils and have re-introduced the crop into organic and conventional farming in Central Europe. The standard cropping system of lentils in Central Europe is mixed cropping with cereals, such as oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.) and rye (*Secale cereale* L.), to avoid lodging of the crop. However, there is little information referring to this region about lentil cultivation under temperate climates from the scientific research. One of the most relevant challenges for lentil growing is increasing its yield, which in practical farming in Germany is currently 0.5-0.8 t lentil grains ha^{-1}. This yield is much lower than the 1-2 t ha^{-1} in, for example, Turkey, Canada and Australia (Tepe *et al.*, 2005; McDonald *et al.*, 2007; Baird *et al.*, 2009), even when the crop is grown in sole cropping in these countries.

Currently, lentils are sown in April/May in the Swabian Alb mountains in SW Germany, a traditional lentil growing area. This allows enough time for false seedbed techniques (several passes to stimulate weed populations to germinate and then control weeds before or as the crop is seeded) to reduce weed pressure, as lentils have low competitive capacity against weeds (Muehlbauer *et al.*, 1981). On the other hand, the comparatively late sowing date shortens the growing season and may be a reason for the low yields. Early sowing (earlier than April/May) can provide more time for crop growth to obtain more accumulation of dry matter, especially under short-day conditions in spring, resulting in potentially higher yields; meanwhile, false seedbed techniques are not possible anymore. As some lentils are reported to show frost-tolerance to a certain extent, Murray *et al.* (1988) ranked lentils as similar to faba beans (*Vicia faba*) and better than peas with respect to winter hardiness in Turkey. Winter hardiness was also described for lentils by Fruwirth (1936), Kusmenoglu and Aydin (1995), and Hamdi *et al.* (1996); therefore an early sowing date might be possible. Thus, it is necessary to explore the potential growth period for lentils to better adapt the cropping system to the temperate climate in Europe.

This study focused on a standard lentil-barley cropping system which has been very common in southwest Germany in recent years. The objective was to identify the optimum sowing time for an existing lentil/barley cropping system with different lentil genotypes in order to increase crop yield and to reduce weed infestation under temperate climatic conditions.

Materials and Methods

Experimental sites

A field experiment was carried out at two sites: the organic research station Kleinhohenheim (“KH”, 48.7° N, 9.2° E and 435 m above sea level), and the conventional research station Oberer Lindenhof (“OLI”, 48.5° N, 9.3° E, 700 m above sea level, in the center of the Swabian Alb mountains) of the University of Hohenheim, southwest Germany, in 2009 and 2010.

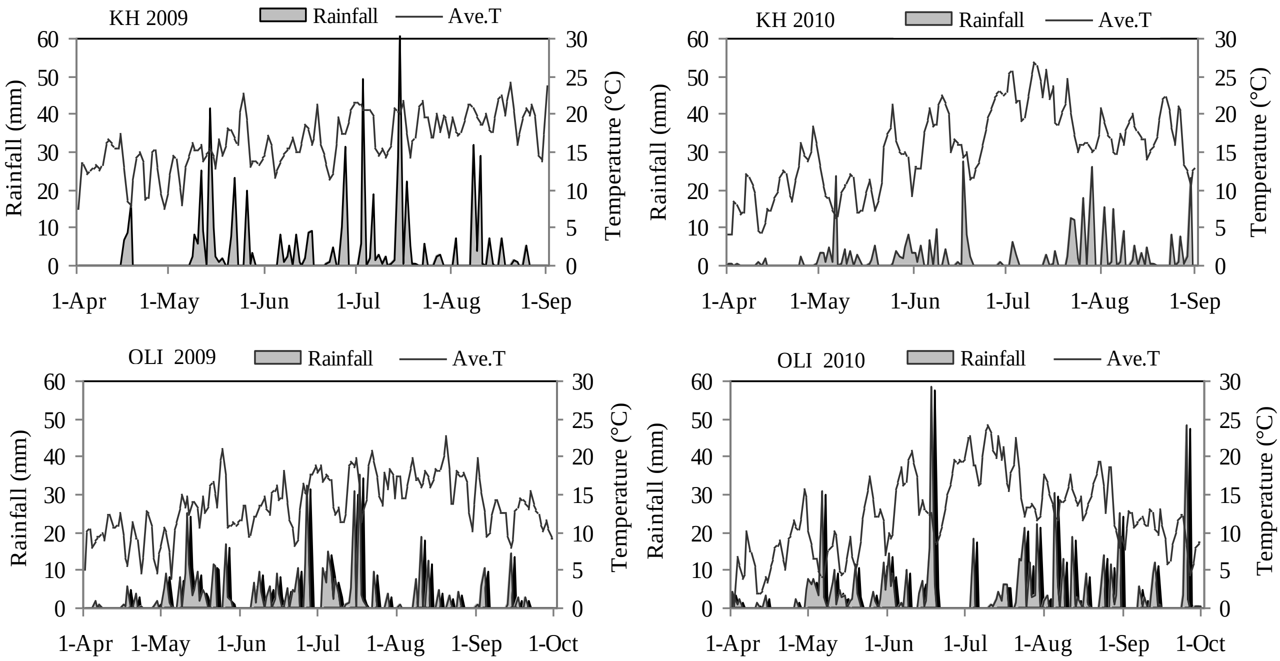

Fig. 1 Total rainfall (mm) and mean temperature (°C) during the lentil growth period in the locations KH (from April to August) and OLI (from April to September) in 2009 and 2010

Location KH is characterized by a long-term (1961-2010) annual average rainfall of 710 mm, and an air temperature of 9.2 °C. In the last six years (2005-2010) in spring, the mean minimum temperatures are -8.8 °C, -8.0 °C and -1.1 °C (February, March, April; respectively). Total rainfall and mean temperature during the lentil growing season from April to August was 601 mm and 16.3 °C in 2009, 362 mm and 15.4 °C in 2010 (Fig.1). The dominant soil types are Luvisols and Cambisols, with loess to sandy loamy clay textures. More detail on the topsoil (0-20 cm) characteristics and the soil mineral nitrogen (nitrate and ammonium fractions) was shown in Table 1. The research station has been managed according to the organic standards of Bioland and Naturland since the year 1993, and has an 8-year crop rotation of grass/clover (two years), winter wheat (*Triticum aestivum* L.), oat (*A. sativa*), faba bean (*V. faba* L.), spelt (*T. aestivum ssp. spelta*), maize (*Zea mays* L.)/potatoes (*Solanum tuberosum* L.), and triticale (*Triticosecale*). The current experiment with lentils was integrated into the faba bean field, thus the preceding crop was oat.

Table 1 Topsoil characteristics and mineral nitrogen content of the experimental sites Kleinhohenheim (KH) and Oberer Lindenhof (OLI)

Item	KH	OLI
Soil pH	7.0	5.1 (2009), 5.6 (2010)
P_2O_5	24 mg/100 g soil	16 mg/100 g soil
K_2O	19 mg/100 g soil	27 mg/100 g soil
MgO	10 mg/100 g soil	11 mg/100 g soil
Mineral N (NH_4-N and NO_3-N, 0-30 cm) in March	9 kg ha^{-1} (2009) 8 kg ha^{-1} (2010)	21 kg ha^{-1} (2009) 19 kg ha^{-1} (2010)
Mineral N (NH_4-N and NO_3-N, 30-60 cm) in March	9 kg ha^{-1} (2009) 6 kg ha^{-1} (2010)	16 kg ha^{-1} (2009) 17 kg ha^{-1} (2010)

Location OLI is characterized by an average long-term (1970-2010) annual rainfall of 942 mm and air temperature of 6.9 °C. In the last six years (2005-2010) in spring, the mean minimum temperatures are -14.4 °C, -11.3 °C and -5.6 °C (February, March and April; respectively). The total rainfall and mean temperature during the growing season of lentils from April to September was 486 mm and 13.1 °C in 2009, 732 mm and 12.5 °C in 2010 (Fig.1). The geologic formation of this region is White Jurassic Delta, and the soil is considered to be argillaceous silt rich in humus. The nutrient status of the experimental site was shown in Table 1. The preceding crops were grassland for pasture in 2009, and wheat in 2010.

The soil pH was determined potentiometrically in a soil suspension of 3 M KCl. Available P and K were extracted by CAL method (Schüller, 1969). Magnesium was determined by the flame atomic absorption spectrometric method (Spectr AA 220FS). Soil mineral N was determined using a flow injection analysis system “FIA star 5012 System”.

Experimental design and data collection

Three sowing dates: early, medium, and late, were tested in both locations (Table 2). These sowing dates referred to the phenological events of flowering of coltsfoot (*Tussilago farfara* L.; T1), dandelion (*Taraxacum officinale* Weber ex F.H. Wigg; T2) and lilac (*Syringa vulgaris* L; T3). Four genotypes of lentil: “Anicia” (green marbled, TKW 31 g), “Schwarze Linse” (black, TKW 20 g), “Hellerlinse” (brown, TKW 62 g) and “Berglinse” (brown coat with red inside, TKW 32 g) were mixed-cropped with spring naked-barley (cv. Hora) at each sowing date. The trial was a split-block design with four replications, with a total number of 48 plots at each location. At KH, individual plots consisted of 16 rows with a row spacing of 15 cm and a length of 4.2 m, while individual plots were 6 rows with 19 cm row spacing and 4.2 m (2009) or 4.0 m (2010) length at OLI. The fixed total target seeding density was 240 seeds m^{-2} with a cropping ratio of lentil:barley = 3:1 in both locations. Crops were sown using a plot drill at a uniform sowing depth of 3 cm and were harvested by hand when the majority of lentil pods had turned to brown and tended to open (Table 2).

Table 2 Sowing dates and corresponding harvest times for a standard lentil-barley mixed cropping system at Kleinhohenheim (KH) and Oberer Lindenhof (OLI) in 2009 and 2010

Location	Sowing date	2009		2010	
		Sowing	Harvesting	Sowing	Harvesting
KH	Early (T1)	07/04	05/08	30/03	04/08
	Medium (T2)	15/04	11/08	16/04	11/08
	Late (T3)	04/05	27/08	29/04	26/08
OLI	Early (T1)	09/04	13/08	07/04	10/08
	Medium (T2)	27/04	01/09	27/04	25/08
	Late (T3)	20/05	17/09	25/05	24/09

Weed density and species were investigated during lentil flowering to early pod formation stage at each sowing date in the location KH (2009 and 2010) and OLI (only 2010), with a sample area of 3 × 0.25 m^2 per plot. No further crop management such as mechanical weed control, fertilization or fungal crop protection was done to mimic the situation of most organic lentil farmers who do not perform direct mechanical weed control, mainly because of the susceptibility of lentils to mechanical damages. The sample area per plot for harvesting was 2 × 0.5 m^2 at KH, and 2 × 0.25 m^2 at OLI. Crops and weeds were pulled up by hand in the sampling area, and then separated by crop species and weeds. Roots of all crops and weeds were cut manually and discarded so that the total aboveground biomass remained for further analyses. Air-dried samples of each plot were threshed using a threshing machine at the speed of 550 rpm for lentils and 850 rpm for barley. For dry weight determination, all the samples were oven-dried for three days at 80°C to a constant weight.

Statistical analysis

An analysis of variance was performed using the “proc mixed” procedure of the SAS statistical software Version 9.2 (SAS Institute, 2009). The sowing date was regarded as the main-plot factor, and lentil genotype as the sub-plot factor. Replication was considered as a random effect while sowing date and lentil genotype were taken as fixed effects. Data were square root transformed to get a normal distribution and homogeneity (Levene’s test) of variance if necessary.

Results

Crop grain yield, biomass and yield components

The different sowing dates, lentil genotypes, experimental years, locations, and their interactions had highly significant effects on the grain yield and aboveground total biomass of lentils (Table 3). Most of the variables and their interactions were also significant for barley grain yield and biomass. The different lentil genotypes had no significant effect on the yield of barley, except for some interactions with year and location.

Table 3 Analysis of variance (Pr>F) for the effects of sowing date (S), lentil genotype (G), experimental year (Y), location (Lo), and their interactions for crops grain yield and aboveground total biomass in a standard lentil-barley mixed cropping system with different lentil genotypes in 2009 and 2010

Factor	DF	Lentil		Barley	
		Grain yield	Biomass	Grain yield	Biomass
S	2	<0.0001	<0.0001	<0.0001	<0.0001
G	3	<0.0001	<0.0001	0.1157	0.0829
Y	1	0.0038	<0.0001	<0.0001	<0.0001
Lo	1	0.0002	0.0025	0.0002	<0.0001
S×G	6	0.0003	0.0032	0.4039	0.2866
G×Y	3	<0.0001	0.0040	0.9262	0.7101
S×G×Y	8	<0.0001	<0.0001	<0.0001	<0.0001
S×G×Lo	11	<0.0001	<0.0001	0.0272	0.2435
S×G×Y×Lo	12	<0.0001	<0.0001	<0.0001	<0.0001

None of the varieties seem to suffer from early sowing, for instance due to cool temperatures. Lentil grain yield and aboveground total biomass decreased with delayed sowing dates in both years and locations, except for OLI 2009 (Fig. 2). An early sowing of lentils resulted in the highest grain yield among the three sowing dates for all genotypes. The genotype Anicia had the highest grain yield in both years and both locations, accounting for about 3.0 t ha^{-1} (2009) and 1.9 t ha^{-1} (2010) at KH, and 1.1 t ha^{-1} (2009) and 2.4 t ha^{-1} (2010) at OLI. The yield of Berglinse was very close to that of Anicia in KH in both years, but this comparison was not observed at OLI. Schwarze Linse yielded less than Anicia, with a range of 1.6-2.1 t ha^{-1} at KH and 0.5-1.7 t ha^{-1} at OLI. Hellerlinse produced the lowest grain yield in both years and both locations. Late sowing caused grain yield losses at KH of 18-55 % compared to the early sowing date, depending on genotype and year. Similarly, grain yield losses at OLI accounted for 17-75 % if the sowing date was later than the earliest date.

Similar to the yield and biomass trends of lentils, the grain yield of barley and aboveground total biomass also dropped when sowing was delayed (Fig. 2). The yield of barley was highest at early sowing with a mean of about 1.0 t ha^{-1} (2009), 0.8 t ha^{-1} (2010) at KH and 2.4 t ha^{-1} (2009), 0.4 t ha^{-1} (2010) at OLI. On average, barley grain yield declined by 28% and 54% (KH), and 13% and 52% (OLI) if early sowing was postponed to medium and late sowing, respectively.

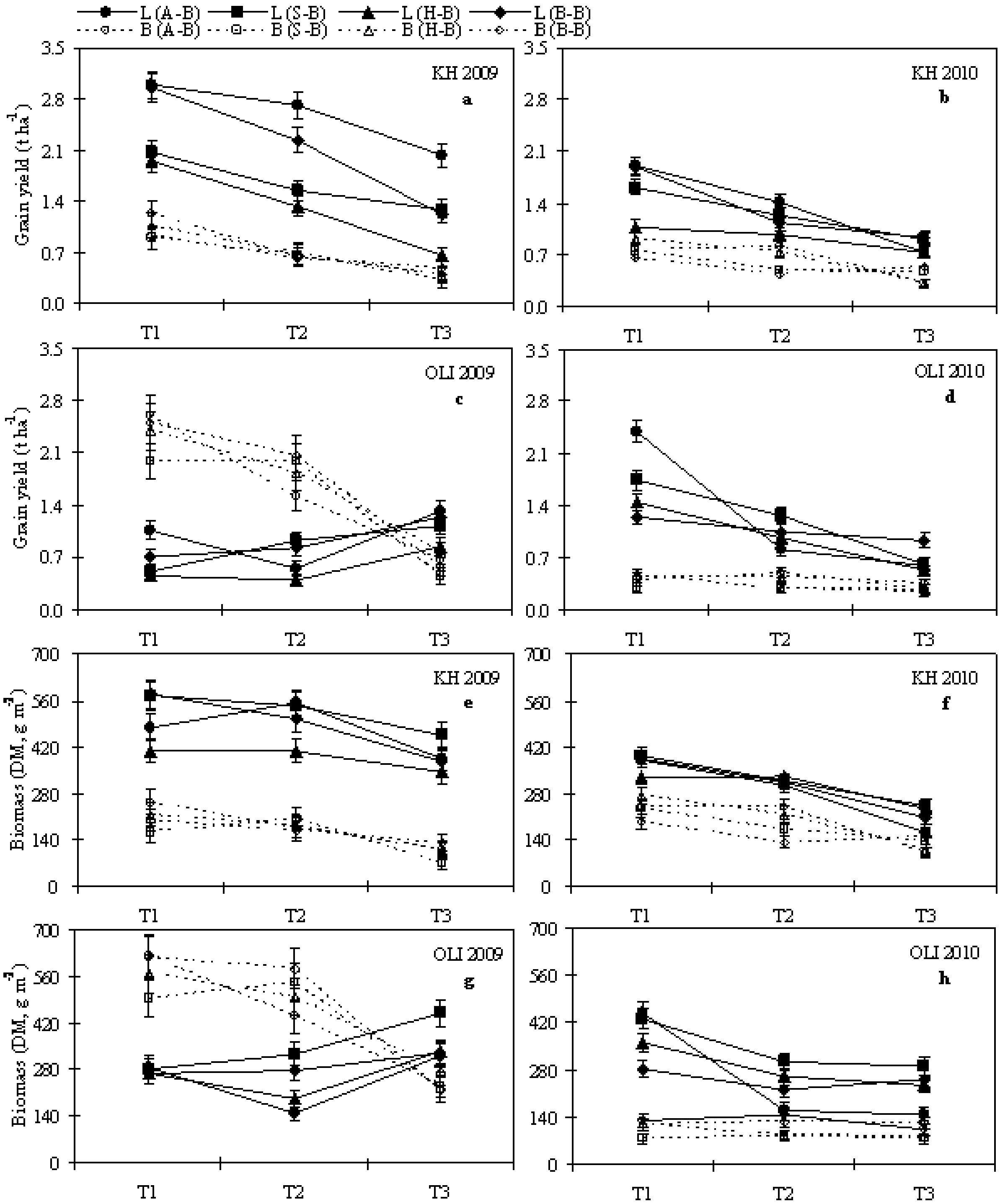

Fig. 2 Lentil (L) and barley (B) grain yields (a, b, c, and d) and aboveground total biomass (e, f, g, and h) in a standard lentil-barley mixed cropping system at three sowing dates (Early "T1", Medium "T2", and Late "T3") in KH and OLI (2009-2010). A-B, Anicia-barley; S-B, Schwarze Linse-barley; H-B, Hellerlinse-barley; B-B, Berglinse-barley. All values are means (n = 4) ±S.E. (bars)

There were variations in the plant density of lentils depending on location, year and genotype; however, different sowing dates had no significant effect on the crop density in general (Table 4). Both lentil seed number per plant (except for OLI 2009) and TKW decreased significantly with delayed sowing date generally, very similar to the trend of lentil grain yield. At location KH, the number of seeds per individual lentil plant declined by 19%-50%, depending on the genotype, if sowing was postponed. The yield components of the companion crop barley (ears m^{-2}, seeds ear^{-1}, and TKW) also decreased significantly with delayed sowing time; however, there were no significant differences in the number of ears and the number of seeds per ear if barley was combined with different lentil genotypes (Table 5).

Table 4 Yield components of four lentil genotypes at three sowing dates (Early "T1", Medium "T2", and Late "T3") in the location KH and OLI in 2009 and 2010.

Location	Genotype	2009			2010		
		Plants m^{-2}	Seeds $plant^{-1}$	TKW (g)	Plants m^{-2}	Seeds $plant^{-1}$	TKW (g)
KH	***A****						
	T1	152 ab	77 a	25.3 ab	154 a	45 a	28.2 a
	T2	177 a	61 b	24.9 b	146 a	37 b	26.7 ab
	T3	132 b	58 b	26.7 a	166 a	18 c	25.8 b
	SL						
	T1	198 a	62 a	17.1 b	174 a	46 a	20.8 a
	T2	183 ab	48 b	17.5 b	176 a	35 b	20.4 a
	T3	149 b	44 b	19.4 a	196 a	23 c	21.1 a
	HL						
	T1	194 a	25 a	40.7 a	168 b	11 a	57.3 a
	T2	179 a	17 b	42.5 a	207 a	9 ab	53.2 b
	T3	172 a	9 c	42.5 a	195 ab	7 b	53.4 b
	BL						
	T1	174 a	71 a	24.4 b	191 a	33 a	30.2 a
	T2	181 a	51 b	24.2 b	158 b	24 b	31.0 a
	T3	153 a	30 c	26.7 a	163 ab	20 b	29.0 a
OLI	***A***						
	T1	155 a	27 a	26.8 a	212 a	43 a	27.0 a
	T2	158 a	12 b	27.8 a	139 b	23 b	27.1 a
	T3	161 a	33 a	26.3 a	118 b	22 b	24.4 b
	SL						
	T1	144 b	24 b	16.6 b	176 a	48 a	21.9 a
	T2	180 ab	28 ab	19.7 a	154 a	38 b	22.2 a
	T3	184 b	34 a	19.2 a	154 a	27 c	14.8 b
	HL						
	T1	166 b	7 ab	50.9 b	125 a	20 a	58.5 a
	T2	209 a	4 b	53.2 a	143 a	13 b	48.8 b
	T3	191 ab	10 a	51.1 ab	140 a	10 b	40.3 c
	BL						
	T1	159 b	19 a	26.5 b	126 a	33 a	30.6 a
	T2	158 b	20 a	28.7 a	141 a	26 b	29.4 a
	T3	198 a	24 a	27.5 ab	129 a	31 ab	24.2 b

Significance (Pr>F)

Factor	DF	Plants m^{-2}	Seeds $plant^{-1}$	TKW	Factor	DF	Plants m^{-2}	Seeds $plant^{-1}$	TKW
S	2	0.5172	<0.0001	<0.0001	S×G	6	0.0497	0.0468	<0.0001
G	3	0.0089	<0.0001	<0.0001	G×Y	3	0.0506	<0.0001	<0.0001
Y	1	0.0033	0.0002	<0.0001	S×G×Y	8	0.0440	<0.0001	<0.0001
Lo	1	0.0090	<0.0001	0.1524	S×G×Lo	11	0.0270	<0.0001	<0.0001
					S×G×Y×Lo	12	<0.0001	<0.0001	<0.0001

*Genotypes: A (Anicia), SL (Schwarze Linse), HL (Hellerlinse), BL (Berglinse). S, sowing date; G, genotype; Y, year; Lo, location. No significant differences for values with the same letters in a column within the same lentil genotype at one location and year, $P<0.05$

Table 5 Yield components of barley at three sowing dates (Early "T1", Medium "T2", Late "T3") in a lentil-barley mixed cropping system with different lentil genotypes at KH and OLI

Location	Genotype mixture	2009 Ears m^{-2}	2009 Seeds ear^{-1}	2009 TKW (g)	2010 Ears m^{-2}	2010 Seeds ear^{-1}	2010 TKW (g)
KH	***A-B****						
	T1	161 a	22	35.5 a	117 a	18	34.9 a
	T2	106 b	17	35.1 a	124 a	19	36.3 a
	T3	73 b	16	34.6 a	72 b	12	37.5 a
	S-B						
	T1	105 a	24	35.8 a	121 a	18	35.2 a
	T2	105 a	17	36.2 a	102 a	14	35.0 a
	T3	59 b	17	31.6 b	84 a	16	35.6 a
	H-B						
	T1	139 a	22	35.2 a	122 a	21	37.6 a
	T2	107 ab	18	35.2 a	125 a	17	35.1 a
	T3	82 b	14	32.4 a	68 b	14	35.0 a
	B-B						
	T1	125 a	21	35.4 a	112 a	16	36.0 a
	T2	101 a	18	35.6 a	85 a	15	34.2 a
	T3	92 a	15	33.2 a	92 a	16	36.8 a
OLI	***A-B***						
	T1	157 a	20	41.5 a	84 a	14	36.1 a
	T2	131 a	15	39.0 ab	100 a	15	35.7 a
	T3	60 b	13	36.5 b	86 a	11	29.3 b
	S-B						
	T1	122 a	20	40.5 a	58 a	14	35.0 a
	T2	163 a	16	38.9 a	64 a	14	35.3 a
	T3	60 b	10	31.0 b	83 a	10	28.4 b
	H-B						
	T1	146 a	20	41.5 a	81 a	16	37.0 a
	T2	153 a	15	40.2 a	68 a	13	34.8 a
	T3	76 b	12	35.5 b	79 a	12	28.1 b
	B-B						
	T1	152 a	20	41.3 a	75 a	16	37.1 a
	T2	180 a	15	39.3 a	92 a	15	35.0 a
	T3	58 b	13	35.1 b	104 a	11	29.6 b

Significance (Pr>F)

Factor	DF	Ears m^{-2}	Seeds ear^{-1}	TKW	Factor	DF	Ears m^{-2}	Seeds ear^{-1}	TKW
S	2	<0.0001	<0.0001	<0.0001	S×G	6	0.3874	0.2191	0.0343
G	3	0.1651	0.9889	0.0380	G×Y	3	0.7016	0.4486	0.8979
Y	1	0.0006	<0.0001	0.0147	S×G×Y	8	<0.0001	0.0006	0.1707
Lo	1	0.3753	<0.0001	0.1650	S×G×Lo	11	0.1368	0.0111	<0.0001
					S×G×Y×Lo	12	<0.0001	0.5977	<0.0001

*A-B, Anicia-barley; S-B, Schwarze Linse-barley; H-B, Hellerlinse-barley; B-B, Berglinse-barley; S, sowing date; G, genotype mixture; Y, year; Lo, location. No significant differences for values with the same letters in a column within the same genotype mixture at one location and year, P<0.05

Weed infestation

The most dominant weed species at KH were *Veronica persica* L., *Cerastium holosteoides* Fries, *Polygonum convolvulus* L., *Galium aparine* L, *Stellaria media* L., *Chenopodium album* L. and *Alopecurus myosuroides* L., with changing proportions in both experimental years. The weed population at OLI was different from that of KH, with *Poa* spp., *V. persica* L., *Lamium purpureum* L. and *Capsella bursa-pastoris* L. being the most abundant species. Some weed species appeared only at the sowing dates T2 and T3, such as *Sonchus asper (*L.*)* Hill, *Trifolium repens* L. and *Matricaria chamomilla* L. at OLI.

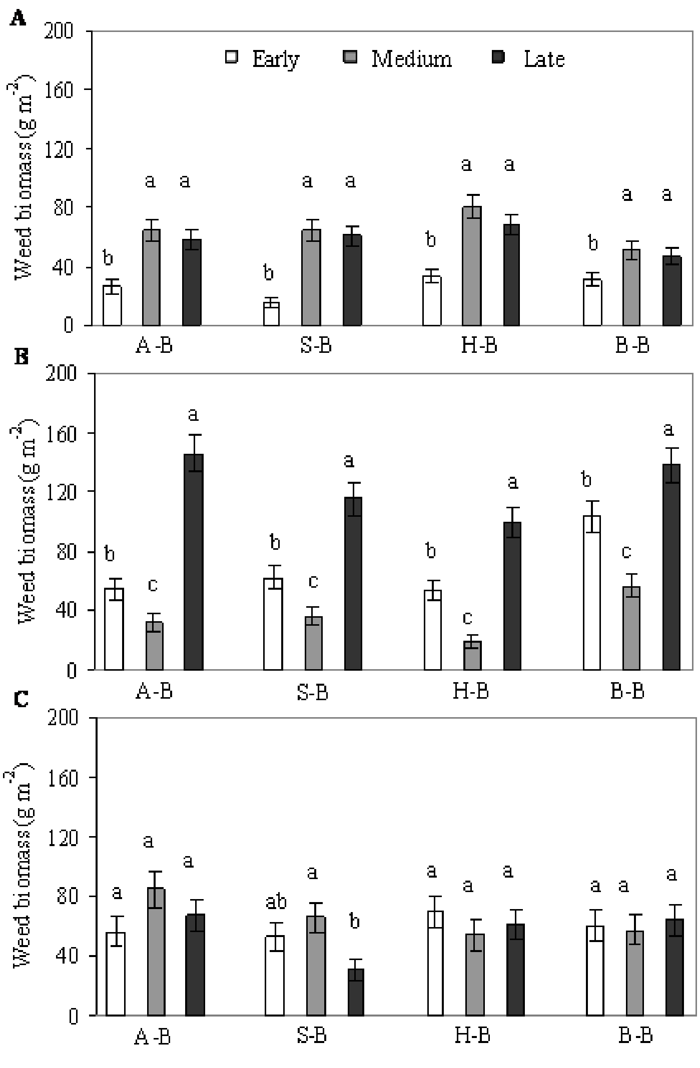

Fig. 3 Weed biomass (DM, g m^{-2}) in a standard lentil-barley mixed cropping system with four lentil genotypes at three sowing dates in the location KH in 2009 (A) and 2010 (B), and the location OLI in 2010 (C).

A-B, Anicia-barley; S-B, Schwarze Linse-barley; H-B, Hellerlinse-barley; B-B, Berglinse-barley. No significant differences for values with the same letters within the same genotype mixture at one location and year, P<0.05. All values are means (n = 4) ±S.E. (bars)

The weed biomass in the crop clearly varied between both years and ranged from 16-81 g DM m^{-2} (2009), 19-145 g DM m^{-2} (2010) at KH and 31-85 g DM m^{-2} (2010) at OLI (Fig. 3). In general, the weed biomass was significantly lower if lentils were sown at T1 (early) as compared to the later sowing dates. This effect was visible for all lentil genotypes. Additionally, there was a negative correlation between weed dry biomass and lentil grain yield in KH ($r = -0.435$, $p<0.001$, data not shown). No clear effect of the sowing date on weed biomass was found at location OLI, except for the genotype Schwarze Linse (data not shown).

The density of weeds (plants m^{-2}) also varied significantly by the sowing date, and additionally varied significantly by the year and location (Table 6).

Table 6 Weed density (plants m^{-2}) in a standard lentil-barley mixed cropping system at three sowing (Early "T1", Medium "T2", and Late "T3") at the locations KH (2009 and 2010) and OLI (2010)

Genotype	KH 2009			KH 2010			OLI 2010		
mixture	T1	T2	T3	T1	T2	T3	T1	T2	T3
A-B*	132 a	118 a	116 a	55 b	89 a	95 a	538 a	315 b	163 c
S-B	121 a	89 b	112 a	60 b	96 a	74 b	561 a	326 b	161 c
H-B	113 a	128 a	127 a	56 b	84 a	73 ab	544 a	301 b	181 c
B-B	134 a	137 a	126 a	60 b	86 a	82 a	516 a	294 b	193 c
Average	125	118	120	58	89	81	540	309	175

Significance (Pr>F)

Factor	DF	Weed density	Factor	DF	Weed density
S	2	<0.0001	S×G	6	0.2099
G	3	0.4166	G×Y	3	0.0726
Y	1	0.0012	S×G×Y	8	<0.0001
Lo	1	<0.0001	S×G×Lo	11	<0.0001

*A-B, Anicia-barley; S-B, Schwarze Linse-barley; H-B, Hellerlinse-barley; B-B, Berglinse-barley; S, sowing date; G, genotype mixture; Y, year; Lo, location. No significant differences for values with the same letters in a row within the same genotype mixture at one location and year, P<0.05

Location OLI had a generally higher weed density than location KH. In contrast to the total weed biomass, the number of weed plants was lower if the lentil/barley mixture was sown on the medium or late date. However, the effects of the lentil genotypes and the interaction of sowing date × genotype on the weed density were not significant. The mean weed density at KH (2009) in four lentil genotypes in the mixed cropping system with barley at T1, T2 and T3 accounted for 125, 118, and 120 plants m^{-2}. A different situation was found for the year 2010 with the early sowing date resulting in the lowest number of 58 weed plants m^{-2} for T1, compared to 89 and 81 plants m^{-2} for T2 and T3. At OLI, the weed density also decreased if the crop was sown later in the year, accounted for 540 (T1), 309 (T2) and 175 (T3) plants m^{-2}.

Discussion

The lentil grain yield of this study was higher than that reported from practical farming in southwest Germany (less than 1 t ha^{-1}, W. Mammel, personal communication), which could be caused partly by the method of harvesting. Hand-harvesting by uprooting the total plants, as performed in the present study, may have resulted in lower grain losses than mechanical harvesting. The total yield from lodging plants may therefore be over-estimated in our study compared with practical farming in temperate climates. However, the yield of lentils in this experiment was similar to yields that can be obtained under semi-arid conditions; for instance, 0.6 – 1.4 t ha^{-1} in organic farming in Greece (Vlachostergios *et al.*, 2011), 1.0 t ha^{-1} up to 2.5 t ha^{-1} in conventional farming in south-western Australia (Siddique *et al.*, 1998), about 1.2 t ha^{-1} in Turkey conventional farming under dryland conditions (Yagmur and Kaydan, 2006), and around 1.5 t ha^{-1} of 10-year average lentil yield in Saskatchewan in Canada (McVicar *et al.*, 2010). Taking into account that the cropping system in the current experiment was mixed cropping, compared to sole cropping in most of the studies from semi-arid conditions, the yields are quite promising and show that the yield potential for German farmers has not yet been achieved.

Annual differences in grain yield can be a result of differences in water supply and temperatures during the critical period from flowering to beginning of pod filling (KH: 601 mm during the lentil growing season 2009, 362 mm during lentil growing in 2010). Water deficit can reduce lentil flower production and seed numbers (Hamdi *et al.*, 1992; Shrestha *et al.*, 2006).

The level of lentil yield was similar in both locations (0.6-3.0 t ha^{-1} in KH and 0.4-2.4 t ha^{-1} in OLI; data not shown), a fact that indicates that lentils can be also grown on “better” sites (KH) and not only on the traditional, poorer sites (such as OLI). A factor contributing to varying yields in both locations could have been the preceding crop which resulted in the weeds and volunteers observed in the following crop of lentils. This was especially true at OLI in 2009, because lentils followed to grassland. The mean loss in yield of winter-sowing lentils caused by weeds could be 60%, or even 100% at the highest density of weeds (Halila, 1995). Additionally, the soil pH at OLI was below the optimum for lentils (around 7.0; Oplinger *et al.*, 1990), and was close to the minimum pH that can be tolerated (Roger, 1987).

Grain yields of lentils and barley were generally reduced if the sowing time was delayed. Sowing at the end of March or at the beginning of April allowed a longer period for crop vegetative and reproductive growth and thus more accumulation of dry matter compared to late sowing. Our results were in line with the studies of Silim *et al.* (1991) and Siddique *et al.* (1998) who both indicated that lentil seed yields declined with delayed sowing in dryland Mediterranean-type environments of south-western Australia, and in northern Syria. As lentils are usually quantitative long-day plants (though some cultivars tend to be day-neutral), they have a quantitative response to photoperiod and flower more quickly during longer days compared to shorter days (Summerfield and Roberts, 1988). Large parts of Europe, with temperate climates, are located at latitudes that experience large annual differences in day length. Thus, early sowing and young growth of the plants under comparatively short-day conditions can increase the growing season, slow down plant development, and increase dry matter and yield production of both lentils and barley which is also sensitive to photoperiod (Guitard, 1960; Takahashi and Yasuda, 1960). The genotype Anicia, which always showed highest yield performance in the experiment, is currently commercially grown in the local area, and seems to be better adapted to local conditions.

Early sowing of lentils was an appropriate method to indirectly control weeds. Except for the grass weed and volunteer infestation in 2009 at OLI, the early sown lentil/barley mixture seemed to suppress emerging weeds efficiently, probably because of higher total biomass production of the crops and increased tillering of the barley, resulting in higher competiveness of the total mixture.

As an indicator to assess the competition of the weed infestation, weed biomass seemed more reasonable than “weed density” in the current study. The strategy of early sowing in order to achieve highly competitive crops seems superior to the strategy of a "false seedbed". Similar to the strategy of increasing lentil competitiveness by higher sowing density and final crop density (Ball *et al.*, 1997; Paolini *et al.*, 2003; Baird *et al.*, 2009), robust and big plants from early sowing can better compete with emerging weeds. It is not yet clear whether this effect is caused by the lentil crop itself, or rather by the companion crop lentil, or maybe a combination of both.

Sowing lentils as early as possible seems a feasible strategy to increase yields and to control weeds, if no other, direct weed control such as hoeing and harrowing can be performed in the standing crop. The genotype Anicia, which is already widely used by growers in the study area, seems to be the most promising genotype in terms of yield, though other genotypes such as Berglinse could be an alternative. The study revealed that "good" sites are also suitable for lentil cultivation, so that many locations can be considered for lentil growing. This means that many organic farmers have an option for to integrate lentils in their crop rotation taking advantage of the beneficial effects of crop biodiversity and N-fixation. Breeding for winter hardiness of lentils for temperate conditions to extend the growth period and further increase yield could be the next step in the story of re-introducing lentils into German organic farming.

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Introduction to Chapter 4

Results from the previous chapter 3 indicated that **early sowing** (end of March or begin of April) was feasible for lentil production in the local area to increase the grain yield of lentils and can also be used as an indirect method of weed control in organic farming where herbicides are not permitted.

Thus, organic lentil growers always have to pay more attention to weed control as the lentil crop has a low capacity for competition against weeds. Lentil mixed cropping can help reducing the weed infestation to some extent, which has also been mentioned in paper 1 and 2. Besides, there are other methods to control weeds. As a by-product from hedgerow cutting, woodchips used for mulching may be a good alternative method to control weeds. This test was implemented in the next chapter.

CHAPTER 4

Effects of Woodchip Mulch and Barley Intercropping on Weeds in Lentil Crops

The paper titled "Effects of woodchip mulch and barley intercropping on weeds in lentil crops" (Authors: L. Wang, S. Gruber & W. Claupein) was published in 2012 in the journal *Weed Research* **52**, 161-168 (DOI: 10.1111/j.1365-3180.2012.00905.x).

This paper presents results of woodchip mulch application on weed control and crop yield in lentil monocropping and lentil-barley mixed cropping systems under organic farming conditions.

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Effects of woodchip mulch and barley intercropping on weeds in lentil crops

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Summary

The effect of woodchip mulch on weed infestation and crop yield of lentil (*Lens culinaris*) was tested in a 2-year field experiment at the organic research station Klein-hohenheim, University of Hohenheim, Germany, in 2009 and 2010. The treatments included no mulch and an amount of 160 m^3 ha^{-1} (fresh matter) woodchips (a mixture of hedgerow shrub species) applied both in spring-sown lentil sole cropping and in lentil–barley mixed cropping systems after the crops were well established. Averaged over the two years, woodchip mulch reduced weed biomass and weed density (plants m^{-2}) in both cropping systems, with a reduction by 43% and 29% (sole), and by 51% and 30% (mixed) respectively. Compared with lentil sole cropping, lentil–barley mixed cropping decreased weed biomass significantly; however, there was no effect on weed density. Lentil grain yield from sole and mixed cropping was 3.0–3.4 t ha^{-1} and 2.1–2.2 t ha^{-1} in 2009 and 1.0–1.1 t ha^{-1} and 0.8–0.9 t ha^{-1} in 2010. Barley grain yield was 1.4 t ha^{-1} in 2009 and 0.7 t ha^{-1} in 2010. Despite decreasing weeds, the mulch did not improve grain yields of lentil or barley in mixed or sole cropping. In conclusion, the combination of woodchip mulch and mixed cropping is useful to reduce weed infestation in cropping systems where chemical or mechanical weed control is not possible and for crops with a low capacity for competition against weeds.

Keywords: *Lens culinaris*, mixed cropping, sole cropping, weeds, organic farming, yield.

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Introduction

Weeds are known to be one of the most significant agronomic problems, especially on organic farms where herbicides are not permitted for weed control. Besides mechanical weed control, use of organic residues as mulch is an alternative method for weed control in agriculture throughout the world (Gupta, 1991). Many studies have reported that mulches conserve soil moisture, moderate soil temperature and reduce weeds (Ashworth & Harrison, 1983; Birzins & Balatinecz, 1984; Powell *et al.*, 1987). Twigs and small stems, as they occur from periodic coppicing of hedgerows and pruning of trees, can be shredded and used for mulching. This application seems to be more reasonable than combustion, because it can close the nutrient cycle in organic farming (Gruber & Claupein, 2008). Previous studies of woodchip mulch focused mainly on trees pruned periodically to mulch the soil in agroforestry systems or in orchards. There is little information on the effect of woodchips in annual crops, especially for a minor crop such as lentils (*Lens culinaris* Medikus).

With high nutritional value and health benefits, lentils are a popular traditional food in Europe (Horneburg, 2006). However, lentils have low competitive capacity against weeds, especially in the early stage of plant development (Muehlbauer *et al.*, 1981). Mechanical weed control is problematic because of

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damage to the lentil shoots and roots attributed to the sensitivity (Stringi *et al.*, 1988) and twining architecture (Muehlbauer *et al.*, 1985) of the crop. Inter-row weeding practices are only possible in situations where the crop is sown in rows wide enough for implements to pass (Brand *et al.*, 2007). Erman *et al.* (2004) evaluated several weed control methods in winter lentil, but on a conventional farm. Woodchip mulch could be an alternative for weed control in organic farming. A beneficial side-effect of this approach would be the saving of ecologically valuable hedgerows in farmland, if they can indirectly yield a profit by mulch production.

Besides the expected advantage of weed control by woodchips, the potential exists for higher crop grain yields. However, it is not clear whether there will be problems, such as nitrogen immobilisation, allelopathic leachates or damage to the crops when the woodchips are applied. In recent years, lentil–barley mixed cropping has been very common and successful in south-west Germany. Therefore, research is necessary to enhance our understanding of the potential for woodchip mulch to contribute a non-chemical method for weed control to this unique cropping system.

To confirm the impacts of woodchip mulch on lentil production in terms of weed infestation and crop yield, a 2-year field experiment was set up. The hypotheses tested were that woodchips would (i) reduce the weed infestation both in lentil sole cropping and lentil–barley mixed cropping systems and (ii) not reduce crop grain yield in either cropping system.

Materials and methods

Experimental location

A field experiment was established at the organic research station Kleinhohenheim (48°43′N, 9°11′E, and 435 m above sea level) of the University of Hohenheim, south-west Germany, in 2009 and 2010. Mean temperature, precipitation and the soil properties of the location are given in Table 1. The research station was managed according to the organic standards of Bioland and Naturland and has an 8-year crop rotation of grass/clover (2 years), winter wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), faba bean (*Vicia faba* L.), spelt (*Triticum spelta* L.), maize (*Zea mays* L.)/potatoes (*Solanum tuberosum* L.) and triticale (× *Triticosecale* Wittm. ex A. Camus.). This experiment with lentil was integrated in the faba bean field, thus the preceding crop was oat in both years.

Several woody species (bushes and trees) which were grown in hedgerows on the farm to increase biodiversity and to provide wildlife habitats were the source for the woodchips. The species were composed mainly of sycamore (*Acer pseudoplatanus* L.), wild cherry (*Prunus avium* L.), sweet mock-orange (*Philadelphus coronarius* L.), goat willow (*Salix caprea* L.), wild privet (*Ligustrum vulgare* L.), European ash (*Fraxinus excelsior* L.), wayfaring tree (*Viburnum lantana* L.), hazel (*Corylus avellana* L.), dogwood (*Cornus sanguinea* L.), European hornbeam (*Carpinus betulus* L.) and dog rose (*Rosa canina* L.) (Gruber *et al.*, 2008). The composition of the woodchips differed by year, depending on the site chosen for coppicing. All stems were cut in a section of trees and shrubs that were dormant in early spring, before March. Small stems which were < 5 cm in diameter were chopped with a disc-wheel chopper. After that, the woodchips were stored in heaps in the field until the experimental application date. Water content of the woodchips was about 45% (Table 1).

Table 1 Climate, soil conditions and characteristics of woodchips in the experimental station

Item	Value
Weather	
Mean April–August temperature (1961–1990)	14.4°C
Mean April–August temperature (2009 and 2010)	16.3°C (2009), 15.4°C (2010)
Rainfall (annual mean, 1961–1990)	697.6 mm
April–August rainfall (2009 and 2010)	601 mm (2009), 362 mm (2010)
Frost-free period (1961–1990)	278 days
Soil conditions	
Soil type	Luvisols and Cambisols
Soil texture	Loam/loess
Soil pH	7.0
P_2O_5	24 mg 100 g^{-1} soil
K_2O	19 mg 100 g^{-1} soil
MgO	10 mg 100 g^{-1} soil
Mineral N (NO_3–N and NH_4–N, 0–30 cm) in March	9 kg ha^{-1} (2009), 8 kg ha^{-1} (2010)
Mineral N (NO_3–N and NH_4–N, 30–60 cm) in March	9 kg ha^{-1} (2009), 6 kg ha^{-1} (2010)
Characteristics of woodchips	
Particle size	70% <1.2 cm, 13% >2.2 cm
Water content	45%

Soil samples were collected in March before sowing to determine the soil properties. The soil pH was determined potentiometrically in a soil suspension of 3 M KCl solution. Available P and K were extracted according to the CAL method (Schüller, 1969). Soil mineral N was determined in the soil samples after extraction with 0.025 M $CaCl_2$ solution, using a flow injection analysis system, the FIA Star 5012 System (Foss Tecator AB, Höganäs, Sweden). Concentrations of mineral N and total P in water samples were analysed colorimetrically by the flow injection FIA Star 5012 System. Potassium was determined using flame photometry (Flammenphotometer Eppendorf ELEX 6361; Dimedis GmbH, Winden, Germany). Magnesium was determined by flame atomic absorption spectrometry (Spectr AA 220FS; Varian Deutschland, Darmstadt, Germany) after extraction with a 0.025 M $CaCl_2$ solution.

Experimental design and data collection

The experiment was set up in a two-factorial (cropping system, mulch application) randomised complete block design with four replicates. Within each factor, two levels (sole cropping or mixed cropping; with mulch or without mulch) were set up. In the mixed cropping system, lentil was mixed with spring naked barley (*Hordeum vulgare* cv. Hora) in a ratio of 3:1 (lentil: barley), referring to the target total seed density (240 germinated seeds per m^2 in the sole or mixed cropping). The amount of woodchips applied was 160 m^3 ha^{-1} (equal to 1.6 cm layer of mulch; fresh matter). Thus, the four treatments in the experiment were lentil sole cropping + no mulch (L), lentil sole cropping + mulch (L_M), lentil–barley mixed cropping + no mulch (LB) and lentil–barley mixed cropping + mulch (LB_M).

The individual plots included 16 rows spaced 15 cm apart, with a length of 4.2 m. Crops were sown using a plot drill at a uniform sowing depth of 3 cm on 23 April (2009) and 20 April (2010). The woodchips were broadcast on the designated plots by hand during the early stage of lentil development (19 May in 2009 and 27 May in 2010; lentil vegetative stage V6–V7, that is, lentil plants with six or seven nodes), and the soil in the plot was totally covered by woodchips. Determination of lentil vegetative and reproductive growth stages was according to the classification method of Erskine *et al.* (1990). Crops and weeds were hand-harvested from 1 m^2 (2×0.5 m^2) from each plot on 7 August 2009 and 11 August 2010, when the majority of lentil pods had turned to brown and begun to open. Lentil, barley and weeds were separated, and the roots of all crops and weeds were cut and discarded. For dry weight determination, all the samples were oven-dried for 3 days at 80°C to a constant weight. Crops dry samples of each plot were threshed using a small threshing machine. Weed density (plants m^{-2}) and species were counted during lentil flowering to early pod formation stage in both years (25 June 2009 and 2 July 2010), in three 0.25 m^2 quadrats per plot. The investigation of weed species was intensified in the second experimental year with a second count (7 August 2010) before crop harvest.

Statistical analysis

The data were analysed by an analysis of variance using the 'proc mixed' procedure in the SAS statistical program version 9.2 (SAS Institute, 2009). Cropping system and mulch were considered as fixed effects, while replication was taken as a random effect. Transformations of the data (log transformed) were applied if necessary to achieve a normal distribution of the data after examining plots of residuals. Pearson correlation coefficients were calculated for weed biomass and lentil grain yield and yield components using the 'proc corr' procedure in SAS.

Results

Weed biomass

Both woodchip mulch and mixed cropping reduced weed biomass. The combination of mulch and mixed cropping resulted in the lowest weed infestation (12.4 g m^{-2} in 2009 and 37.6 g m^{-2} in 2010; Table 2), compared with the highest weed infestation (118 g m^{-2}) in lentil sole cropping without mulch in the year 2010. Final weed biomass, however, differed between years. The application of woodchip mulch reduced weed biomass by approximately 75% (in sole cropping) and 56% (in mixed cropping) in 2009 and by 10% (sole cropping) and 47% (mixed cropping) in 2010. Averaged over the two experimental years, mulching with woodchips reduced weed biomass by 43% in lentil sole cropping and by 51% in lentil–barley mixed cropping. Mixed cropping instead of sole cropping reduced weed biomass by 56% with no mulch and by 58% with 160 m^3 ha^{-1} woodchip mulch.

Weed density and species

Total weed density (plants m^{-2}) in both years decreased in lentil sole cropping and mixed cropping by woodchip mulch, by 41% and 17% in 2009 and 2010 (sole), 31% and 28% in 2009 and 2010 (mixed) (Table 3). Compared with lentil sole cropping, lentil–barley mixed cropping did not reduce the total weed density in either year. There was no interaction of mulch and cropping system on total weed density.

The numbers of weed species found in the field were 14 and 11 in 2009 and 2010, respectively, and all of them were annual broad-leaved weeds except for one annual grass *Alopecurus myosuroides* Huds. in 2009. In the first experimental year, *Veronica persica* Poir was the most abundant species at more than 60 plants m^{-2}, which was about 67% of the total weed density. *Galium aparine* L. and *Galeopsis tetrahit* L. averaged 8–12 plants m^{-2}.

Table 2 Weed biomass in lentil sole and lentil–barley mixed cropping systems with or without woodchip mulch in 2009 and 2010, with corresponding table of significance

Treatment	Cropping system	Mulch	Weed biomass (g DM m^{-2}) 2009	2010
L	Lentil sole	Without	101.9 (5.51)	118.3 (41.10)
L_M	Lentil sole	With	25.0 (1.35)	106.6 (47.47)
LB	Lentil–barley mixed	Without	27.9 (1.51)	71.1 (29.07)
LB_M	Lentil–barley mixed	With	12.4 (0.67)	37.6 (14.41)
Significance				
Source		d.f.	$P > F$	
Year (Y)		1	0.003**	
Cropping system (C)		1	0.005**	
Mulch (M)		1	0.013*	
C × M		1	0.75	
Y × C		1	0.56	
Y × M		1	0.07	

Significance level: *$P < 0.05$; **$P < 0.01$; values in parentheses are the standard error of mean (SEM), with 9 error degrees of freedom (d.f.).

Table 3 Weed density (plants m^{-2}) in lentil sole and lentil–barley mixed cropping systems with or without woodchips mulch in 2009 and 2010, with corresponding table of significance

Treatment	Cropping system	Mulch	Weed density (plants m^{-2}) 2009 (25 June)	2010 (2 July)	2010 (7 August)
L	Lentil sole	Without	158.0 (15.03)	107.9 (7.69)	80.8 (10.11)
L_M	Lentil sole	With	93.1 (8.86)	88.5 (6.31)	68.2 (8.54)
LB	Lentil–barley mixed	Without	162.8 (15.49)	131.7 (9.39)	103.8 (12.99)
LB_M	Lentil–barley mixed	With	112.2 (10.68)	100.0 (7.13)	70.0 (8.75)
Significance					
Source		d.f.	$P > F$	$P > F$	$P > F$
Cropping system (C)		1	0.28	0.05	0.29
Mulch (M)		1	0.001	0.01	0.04
C × M		1	0.43	0.60	0.38

Values in parentheses are the standard error of mean (SEM), with 9 error d.f.

Other weeds, in numbers mostly below eight plants m^{-2}, were *Sonchus asper* Hill, *Lamium purpureum* L., *Capsella bursa-pastoris* Med., *Chenopodium album* L., *A. myosuroides*. The dominant weed species in 2010 were *Matricaria chamomilla* L., *C. album*, *Stellaria media* (L.) Vill., *V. persica* and *C. bursa-pastoris*, at 13–38 plants m^{-2}. No perennial weeds were present in either year.

Crop grain yield and yield components

Woodchip mulch did not reduce grain yield, crop biomass or yield components. There was no significant mulch × cropping system interaction (Table 4). The lentil yield differed between experimental years and between cropping systems. Compared with sole cropping, the harvest index (HI) of lentils was higher under mixed cropping, whereas the numbers of plants m^{-2} were lower.

The grain yield of barley in the lentil–barley mixed cropping system was 1.4 t ha^{-1} in 2009 and 0.7 t ha^{-1} in 2010 (Table 4). There was a significant difference between the years for barley yield and yield components. However, the woodchip mulch did not have an effect on barley grain yield, biomass or yield components.

Correlations between weed infestation and lentil yield

Relationships between weed infestation parameters and lentil yield in the specific cropping systems (sole or mixed) were explored through Pearson correlation analysis (Table 5). Weed biomass correlated negatively with lentil grain yield and with lentil biomass, both in lentil sole cropping and in lentil–barley mixed cropping systems ($r = -0.63$). However, weed density was not correlated with lentil grain yield or to lentil biomass in either cropping system.

Table 4 Lentil and barley grain yields (DM, t ha^{-1}), aboveground biomass (DM, t ha^{-1}) and yield components in lentil sole and lentil–barley mixed cropping systems with or without woodchips mulch in 2009 and 2010, and the corresponding probabilities of F values from the statistical analysis

Year	Treatment	Cropping system	Mulch	Grain yield L	Grain yield B	Biomass L	Biomass B	HI L	HI B	Plants (or ears) m^{-2} L	Plants (or ears) m^{-2} B	Seeds plant^{-1} (or ear^{-1}) L	Seeds plant^{-1} (or ear^{-1}) B	TKW (g) L	TKW (g) B
2009	L	Lentil sole	Without	3.0 (0.13)		7.2 (0.42)		0.41 (0.02)		204 (7.8)		63.3 (1.20)		23.1 (0.41)	
	L_M	Lentil sole	With	3.4 (0.14)		8.1 (0.47)		0.42 (0.02)		218 (8.3)		64.9 (1.24)		24.4 (0.44)	
	LB	Lentil–barley mixed	Without	2.1 (0.09)	1.4 (0.07)	3.9 (0.22)	3.6 (0.16)	0.50 (0.03)	0.38 (0.02)	160 (6.1)	219 (23.8)	53.7 (1.02)	18.1 (0.85)	24.4 (0.44)	33.9 (0.73)
	LB_M	Lentil–barley mixed	With	2.2 (0.09)	1.4 (0.07)	4.3 (0.25)	3.6 (0.16)	0.48 (0.03)	0.39 (0.02)	165 (6.3)	217 (23.6)	54.2 (1.03)	17.5 (0.82)	24.5 (0.44)	33.5 (0.72)
2010	L	Lentil sole	Without	1.1 (0.15)		3.1 (0.23)		0.37 (0.03)		210 (21.9)		21.4 (3.46)		25.7 (0.41)	
	L_M	Lentil sole	With	1.0 (0.13)		2.8 (0.22)		0.35 (0.03)		188 (19.5)		21.1 (3.41)		25.2 (0.40)	
	LB	Lentil–barley mixed	Without	0.8 (0.10)	0.6 (0.05)	2.0 (0.15)	2.1 (0.22)	0.40 (0.03)	0.31 (0.02)	157 (16.3)	108 (14.8)	20.5 (3.32)	16.3 (1.36)	25.2 (0.40)	36.8 (0.72)
	LB_M	Lentil–barley mixed	With	0.9 (0.12)	0.7 (0.05)	2.2 (0.17)	2.1 (0.22)	0.43 (0.03)	0.31 (0.02)	128 (13.3)	110 (15.0)	28.7 (4.64)	16.5 (1.38)	25.3 (0.41)	36.1 (0.70)
Significance (P > F)															
Source															
Year (Y)				< 0.001	< 0.001	< 0.001	0.002	0.01	0.02	0.10	< 0.001	< 0.001	0.27	< 0.001	0.01
Cropping system (C)				0.001		< 0.001		0.01		< 0.001		0.82		0.45	
Mulch (M)				0.48	0.74	0.26	0.84	0.96	0.87	0.35	0.98	0.30	0.91	0.37	0.49
C × M				0.44		0.42		0.76		0.61		0.34		0.55	
Y × C				0.18		0.01		0.93		0.51		0.09		0.15	
Y × M				0.45	0.84	0.25	0.99	0.84	0.89	0.09	0.93	0.40	0.74	0.14	0.86

HI, harvest index; TKW, thousand kernel weight; Plants m^{-2} and seeds plant^{-1} were counted only for lentils, ears m^{-2} and seeds ear^{-1} were counted only for barley; values in parentheses are the standard error of mean (SEM), with 9 error d.f. (lentil) and 3 error d.f. (barley).

Table 5 Pearson correlation coefficients (r) between weed infestation and lentil yield in lentil sole cropping (above the diagonal) and in lentil–barley mixed cropping systems (below the diagonal)

	Weed biomass	Weed density	Lentil grain yield	Lentil biomass	HI
Weed biomass	1.00	0.21 ns	−0.63*	−0.62*	−0.28 ns
Weed density	0.01 ns	1.00	0.27 ns	0.23 ns	0.23 ns
Lentil grain yield	−0.63*	0.36 ns	1.00	0.98**	0.56*
Lentil biomass	−0.63*	0.33 ns	0.94**	1.00	0.39 ns
HI	−0.27 ns	0.25 ns	0.87**	0.81**	1.00

HI, harvest index.
Significance level: $*P < 0.05$; $**P < 0.001$; ns, not significant.

Discussion

Weed suppressing effect

The application of woodchips reduced the weed infestations (weed biomass and weed density) in lentil sole and mixed cropping systems in both years. Our results support previous studies where woodchip cover, straw mulch and other organic mulches were used for weed control in perennial crops (Jodaugiene *et al*., 2006). The extent of weed suppression by mulch is related to its persistence on the ground (Kamara *et al*., 2000). Some studies (Tian *et al*., 1992; Vanlauwe *et al*., 1996) have found that mulch materials with high nitrogen, low lignin and polyphenol content decomposed faster than mulch materials that were rich in lignin. Furthermore, several studies have described the inhibitory effects of woodchip eluate on germination of lettuce seeds (Rathinasabapathi *et al*., 2005) or on oilseed rape and two species of weeds (*A. myosuroides* and *Papaver rhoeas* L.) seeds (Gruber *et al*., 2008). Inhibitory effects varied, depending on weed or crop species or the woodchip composition. The material composition of woodchips varied by year, depending on the site chosen for pruning. This might be one reason why woodchip mulch worked better in 2009.

The time of mulching may have influenced weed emergence, density and competitive capacity. Physical effects, such as the reduction of light penetration by woodchips because of its low pore volume (Teasdale & Mohler, 2000), may have affected seed germination. Additionally, some studies (Rathinasabapathi *et al*., 2005; Gruber *et al*., 2008) also showed that the allelopathic effects preventing seed germination by woodchips mulch can occur under controlled conditions in the absence of the adsorptive effects of soil.

Little information regarding the optimal timing to apply the woodchips mulch on lentils was found. On the basis of the study by Mohammadi *et al.* (2005) who reported that the critical period of weed interference in chickpea was 17–49 days after crop emergence, and the mulching on lentils in this study was applied 2–3 weeks after crop emergence. This timing was considered optimal to minimise any allelopathic effect on lentils and also to reduce the risk of introducing exotic plant pathogens, which may inhabit the woodchips. The options of applying woodchips immediately after sowing or increasing the amount of mulch to the maximum (without harming the crops) may be viable management options to enhance the level of weed control. The competitive ability of the crop against weeds may have been reduced in the second year of this experiment, because of poor crop development of both the lentil and barley crops. The combined effect of greater weed biomass and dry conditions could have caused substantial yield reduction in 2010. Lentils grow slowly in the early season and are considered to be poor competitors against weeds (Muehlbauer *et al*., 1981). However, if lentils were grown together with a companion crop, such as barley in this study, weed pressure may have been reduced, even in years unfavourable for lentils, compared with sole cropping (Carr *et al*., 1995). Nevertheless, barley can be more competitive against the lentils than the weeds. If a grower's aim is high lentil yields, then the use of woodchip mulch would be the better option.

Lentil yield

Lentil yield may be influenced by the timing of woodchip mulch application, water supply and temperature during the critical period from lentil flowering to beginning of pod filling. As previous research has pointed out, lentil flower production could be reduced by a water deficit (Shrestha *et al*., 2006). In this study, the growing season for lentils was drier in 2010 (362 mm rainfall) than in 2009 (601 mm rainfall), and the rainfall from June to July in the second year was only 169 mm, which may be insufficient for lentils. The effect of increasing soil moisture by woodchip mulch was limited in such a situation. The grain yield in this study was much higher than that reported from commercial farms in south-west Germany (i.e. < 1 t ha^{-1}, W. Mammel, pers. comm.). This may be attributed to differences in harvest methods. Hand-harvesting, as was carried out in this study, would result in less yield loss compared with field-based mechanical harvesting.

The use of woodchip mulch did not result in a yield reduction in this study. A similar result was reported by Gruber *et al.* (2008) in a long-term field experiment applying woodchips within one 7-course crop rotation at the same location. In addition, other studies have reported a yield increase when woodchips were used as a mulch for sorghum (Chiroma *et al.*, 2006), tomatoes (Soumare *et al.*, 2002) and apples (Szweczuk & Gudarowska, 2004). Although the woodchip mulch did not affect crop yield in this study, it did suppress weeds, and because weed seed production in annuals is correlated highly with weed biomass, it reduced the seed input to the soil. This potentially benefits succeeding crops in the rotation. Moreover, mulching might be a good option for soil protection and improvement in the longer term. Soil moisture content can be conserved successfully by straw mulch in no-till or minimum-till systems in USA, Canada and India (Fuentes *et al.*, 2003; Malhi & Lemke, 2007; Singh *et al.*, 2011; Sharma *et al.*, 2011), which is important especially in dry years, in regions with low rainfall or in soils with low water-holding capacity. Woodchip mulch may also be a viable option to help reduce the risk of soil erosion on hilly areas (low slope) in wet years. Because the area of hedgerows on a farm is usually limited, the amount of woodchips as a by-product from hedgerow management does not seem great enough to mulch all arable land of a farm (Gruber & Claupein, 2008). Woodchips could be applied with priority to the area with slopes to decrease soil erosion, or to crops such as lentils with low competition capacity against weeds.

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Introduction to Chapter 5

Results from the previous chapter 4 clearly indicate that **woodchip mulch** had a positive effect on weed suppressing in both cropping systems (lentil monocropping and lentil-barley mixed cropping). The combination of mixed cropping and mulch application achieved even better effects. Although the crop yield was not increased by woodchip mulch, this remains a considerable option for some organic growers applying mulch in small areas where weeds infestation occurs severely.

Besides crop grain yield and weed control, seed quality is another important issue for farmers. In lentil mixed cropping systems, it can be expected that different mixing ratios will affect the seed crude protein content, especially for the two cereals (barley and wheat). So, this part was implemented in the next chapter.

CHAPTER 5

Mixed Cropping with Lentils Increases Grain Protein of Wheat and Barley

The paper titled “Mixed cropping with lentils increases grain protein of wheat and barley” (Authors: L. Wang, S. Gruber & W. Claupein) was submitted to the journal *Experimental Agriculture* in March, 2012 (http://journals.cambridge.org/action/displayJournal?jid=EAG).

The study tested the effect of different mixing ratios on seed quality (crude protein content and thousand kernel weight) of two cereals (wheat and barley) and their companion crop lentils. Main results of the study from a 2-year field experiment (2009 and 2010) showed clearly that seed crude protein content of cereals increased significantly when their proportion was reduced in the mixture grown with lentils. Thus, cereal-lentil mixed cropping can be an option to achieve a high protein content of wheat for improving the breadmaking quality.

Abstract

Spring wheat (*Triticum aestivum*) and spring barley (*Hordeum vulgare*) were mixed cropped with lentils (*Lens culinaris*) in five seeding ratios (100:0, 75:25, 50:50, 25:75, 0:100) at the Experimental Station for Organic Farming Kleinhohenheim, SW Germany in the years 2009 and 2010. Aim of the study was to test the effect of different mixing ratios on seed quality (crude protein: CP, and thousand kernel weight: TKW) of cereals and lentils. Seed crude protein of cereals increased significantly when their proportion was reduced in the mixture with their companion crop lentil. Wheat crude protein increased from 10.3 % DM (2009) and 11.0 % DM (2010) in monocropping to 11.5 % DM (2009) and 15.1 % DM (2010) in mixed cropping with 75 % lentils. Barley crude protein increased in the same way from 13.7 % DM in monocropping to 15.8 % DM in mixed cropping with 75 % lentils. The percentage of CP in lentils, however, did not differ significantly across all mixing ratios. The TKW of cereals and lentils also increased significantly when their share in the mixture was lower. Generally, the total crude protein yield (one cereal plus lentils) in mixtures was significantly higher than that in cereals or lentils monocropping. Mixed cropping with lentils can thus be an option to obtain a high protein content of wheat which is important for a suitable breadmaking quality, particularly in organic farming. If barley is used for feed or food, a high protein content in mixed cropping with lentils is also welcome. On the other hand, malting barley seems not a suitable partner for mixed cropping with lentils as the protein content is higher than in barley monocropping.

Keywords: Breadmaking quality; Crude protein; *Lens culinaris*; Malting barley; Mixing ratio; *Triticum aestivum*

Introduction

High-quality of cereal grains with high crude protein content is wanted for food processing e.g. for a good breadmaking quality of wheat, or for a high nutritional value in general. Unlike wheat (*Triticum aestivum* L.) which is mainly used as a staple food, barley (*Hordeum vulgare* L.) with high protein content is often used for animal feed, and barley with low protein content is wanted as malting barley for beer making. The crude protein content of malting barley is crucial for the malting process, the fermentation period, beer foaming ability, taste and other characteristics (Jones, 2005). Additionally, the uniformity of the barley grains and the grain size and shape is also important. The optimal crude protein in malting barley should be 9-11% (Líšková *et al.*, 2011), or < 11.5% respectively (Aufhammer, 2003).

The seed protein content of many crops depends on the variety (Mosse and Baudet, 1983; Guarda *et al.*, 2004), but can also be highly influenced by environmental conditions and agronomy practices (Erekul and Köhn, 2006). It is generally a challenge in organic farming to increase the grain protein of cereals because readily available, chemical-synthetical fertilizers are not permitted and thus a targeted, late application of nitrogen (e.g. at the stage of heading) is not possible. Hence, it is necessary to find alternative solutions, such as mixed cropping of cereals with legumes. Lentils (*Lens culinaris* L.) with high nutritional value are a traditional and popular food in Europe (Horneburg, 2006). The crop was neglected in farming systems particularly in Germany for many years, but has now a renaissance with increasing acreage. As lentils need a companion crop to avoid lodging under Central European conditions, cereals (mainly barley) are often mixed with lentil. The objective of the study was to evaluate whether different mixing ratios of lentils and wheat or barley affect seed crude protein content and thousand kernel weight.

Materials and Methods

Location, climate and soil

A two-year field experiment was carried out at the organic research station Kleinhohenheim (48° 43' N, 9° 11' E, and 435 m above sea level) of the University of Hohenheim, Southwest Germany, in 2009 and 2010. The long-term (1961-2010) annual average rainfall is 710 mm, with about 377 mm between April and August (Table 1). Luvisols and Cambisols are the dominant soil types of the location, with loess to sandy loamy clay textures. Characteristics of topsoil (0-20 cm) were: pH 7.0, P_2O_5 24 mg, K_2O 19 mg, and MgO 10 mg/100 g soil in 2008. Soil mineral nitrogen (NH_4-N + NO_3-N) was determined before sowing in March and was about 9 kg ha^{-1} in both 0-30 cm and 30-60 cm soil layers in 2009, or 8 and 6 kg ha^{-1} in 2010, respectively.

Table 1 Rainfall and average temperature during the growing season of mixed cropping systems of lentils, spring wheat and spring barley at the experimental station Kleinhohenheim, SW Germany

Month	Rainfall (mm)			Temperature (°C)		
	2009	2010	1961-2010	2009	2010	1961-2010
April	32.2	7.4	51.3	12.6	10.1	8.9
May	162.4	83.8	82.3	15	11.4	13.3
June	95	70.4	89.2	16.2	17.5	16.4
July	215.6	99	79.2	18.5	20.8	18.3
August	95.4	100.9	75.3	19.3	17.2	17.8
April-August	601	362	377	16.3	15.4	14.9
Annual			710			9.2

The research station has been managed according to the organic standards of Bioland and Naturland since 1993, and an 8-year crop rotation of grass/clover (two years), winter wheat (*T. aestivum*), oat (*Avena sativa* L.), faba bean (*Vicia faba* L.), spelt (*Triticum spelta* L.), maize (*Zea mays* L.)/potatoes (*Solanum tuberosum* L.), and triticale (×. *Triticosecale* Wittm. ex A. Camus.) was performed. The current experiment with lentils was integrated in the faba bean field, therefore the preceding crop was oat in both years.

Treatment, crop management and measurement

Lentil (L, cv. Anicia) was mixed cropped with spring wheat (W, cv. Triso which belongs to the class E-Wheat (protein content > 14 %)) or spring naked barley (B, cv. Hora) in five ratios: 100 % L, 75 % L +25 % W (B), 50 % L +50 % W (B), 25 % L +75 % W (B), 100 % W (B). The target crop density for all cropping systems was 240 plants m^{-2}. The current experiment originated from a field trial in which lentil was mixed cropped with five spring-sown companion crops: naked-barley, wheat, oat, linseed (*Linum usitatissimum* L.) and buckwheat (*Fagopyrum esculentum* L.) in five proportions (see above). To test whether mixing ratios had effects on seed crude protein, we focused on two mixtures lentil-barley and lentil-wheat in this study. The original experiment was a Graeco-Latin Square design with three replicates.

The individual plot was 4.2 m in length, with 16 rows in an inter-row distance of 15 cm. The crops were sown uniformly with a 3 cm sowing depth using a plot drill on 23 April (2009) and 20 April (2010). There was no further crop management (e.g. mechanical weed control or fertilizer applying) performed in the field. Hand harvesting was done by pulling up the plants of the sample area 1 m^2 (2 × 0.5 m^2) per plot on 18-21 August (2009) and 16-20 August (2010) when the majority of lentil pods had turned to brown and begun to open. After separation of lentils and wheat (or barley) plants, roots of all crops were cut off and only the aboveground parts were for further analysis. The samples were oven-dried at 80°C to a constant weight (over three days) and then were threshed indoors by a small experimental threshing machine. To determine the seed crude protein, the whole grains of dry samples were milled on a Cyclotec 1093 centrifugal mill (Tecator AB, Hoganas, Sweden). The seed nitrogen content (N % in dry matter; DM) was determined in grain samples using a Vario Max CNS analyzer (Elementar, Hanau, Germany) according to the Dumas Method (Dumas, 1962). Seed crude protein content was calculated by the N content multiplied with the factor 5.7 for wheat (Teller, 1932) and the classical 6.25 factor was used for barley and lentils.

Statistical analysis

Analysis of variance with the factors ratio (R) and year (Y) was performed using the MIXED procedure of SAS version 9.2 (SAS Institute, 2009). Two cereals (wheat and barley) crude protein content and other indices (e.g. seed N content and TKW) were analyzed separately with ignore the original block design. Data were log transformed to get a normal distribution and homogeneity of variance. For letter description, a multiple *t*-test was made only the *F*-test was significant.

Results

Seed crude protein (CP) of either wheat or barley increased significantly when their ratios in mixed cropping with lentils were reduced. The wheat crude protein content in mixed cropping ranged from 10.9-11.5 % DM (2009) and 11.6-15.1 % DM (2010) compared to 10.3 % DM (2009) and 11.0 % DM (2010) in monocropping (Table 2). Barley crude protein was 14.5-15.8 % DM in mixed cropping compared to 13.7 % DM in monocropping (two years average). Generally, mixtures with the lowest proportion of wheat or barley (25 %) resulted in highest crude protein content in the grains, with an increase of 25 % (wheat) or 15 % (barley) CP than that in monocropping systems respectively. The protein content of lentil was not affected by the mixing ratio and varied from 27.2 % to 27.7 % DM. All crops (cereals and lentils) obtained significantly higher seed N content and crude protein in the year 2010 compared to 2009 in the study. The mixing ratio also significantly affected the thousand kernel weight (TKW) of cereals and lentils: the lower the proportion of a crop in the mixture, the higher was the TKW.

Table 2 Seed N content (N %), crude protein (CP, % dry matter) and thousand kernel weight (TKW, g) of crops in lentil-wheat and lentil-barley cropping systems with different mixing ratios over two years (2009-2010) in organic farming

	Wheat 2009			Wheat 2010			Barley			Lentils		
Source	N %	CP[†]	TKW	N %	CP	TKW	N %	CP	TKW	N %	CP	TKW
Ratio (R, %)												
25	2.0 a	11.5 a	36.2 a	2.6 a	15.1 a	37.6 a	2.5 a	15.8 a	35.2 a	4.3	27.2	25.9 a
50	2.0 a	11.5 a	36.6 a	2.2 b	12.8 b	34.0 b	2.4 b	14.9 b	34.6 a	4.4	27.7	25.1 b
75	1.9 ab	10.9 ab	36.1 a	2.0 c	11.6 c	31.2 c	2.3 b	14.5 b	34.8 a	4.4	27.6	25.7 ab
100	1.8 b	10.3 b	35.2 a	1.9 c	11.0 c	31.2 c	2.2 c	13.7 c	33.3 b	4.4	27.4	25.5 ab
Year (Y)												
2009							2.2 b	13.5 b	33.8 b	4.2 b	26.4 b	25.6
2010							2.6 a	16.0 a	35.2 a	4.6 a	28.5 a	25.6

Significance (Pr>F)

	Wheat			Barley			Lentils		
Factor	N %	CP	TKW	N %	CP	TKW	N %	CP	TKW
R	<0.001	<0.001	0.007	0.002	0.002	0.04	0.12	0.11	0.03
Y	<0.001	<0.001	0.002	<0.001	<0.001	0.009	<0.001	<0.001	0.91
R×Y	0.001	0.001	0.02	0.09	0.09	0.34	0.08	0.08	0.71

[†]Crude protein (CP) = N content × 6.25 (barley), Crude protein (CP) = N content × 5.7 (wheat). No significant differences for values followed by the same letters in the column within the same crop, $P<0.05$.

Total crude protein yield (TCP, lentils plus one cereal crop) in each cropping system differed significantly with cropping (lentil-wheat or lentil-barley), mixing ratio, ratio × cropping interactions, and experimental year (Table 3). The mixture of 75 % lentil + 25 % cereals got the highest TCP among five ratios, with the value of 55.9 g m^{-2} in lentil-wheat and

46.0 g m^{-2} in lentil-barley cropping systems, compared with the lowest TCP content in cereal crops monocropping (35.0 g m^{-2} and 21.6 g m^{-2}, respectively). Generally, the TCP in three mixtures were significantly higher than that in cereals or lentil monocropping.

Table 3 Total crude protein yield (TCP, lentils plus one cereal crop) in lentil-wheat and lentil-barley mixed cropping systems with different mixing ratios (lentil:cereal) over two years (2009-2010) in organic farming

Source	Value (TCP, g m^{-2})		
Interaction (ratio × cropping)			
Ratio	Cropping (lentil-wheat)	Ratio	Cropping (lentil-barley)
100:0	39.5 b[†]	100:0	39.5 b
75:25	55.9 a	75:25	46.0 a
50:50	51.4 a	50:50	39.8 b
25:75	49.7 a	25:75	34.5 c
0:100	35.0 c	0:100	21.6 d
Significance (Pr>F)			
Factor	DF	TCP	
Cropping (C)	1	<0.001	
Ratio (R)	3	<0.001	
Year (Y)	1	<0.001	
R×C	3	0.004	

[†]No significant differences for values followed by the same letters in the column within the same cropping system, P<0.05.

Discussion

High crude protein content of wheat or barley could be obtained when the proportion of the cereals in the mixture with lentils was low (25%). The results agreed with the study of Pflaum *et al.* (2011) who reported that malting barley showed higher crude protein (13.8%) in mixed cropping with lentils at a ratio of 3:1 (lentil:barley) than in an 1:1 ratio (12.5%) or in monocropping (11.2%). Similar results were found in mixtures of winter wheat and grain legumes (pea (*Pisum sativum* L.) and faba bean) (Hof *et al.*, 2006) and barley-narbon vetch (*Vicia narbonensis* L.) mixed cropping (Azizi *et al.*, 2011). A reduction of the ratio of cereals in the mixture means a decrease of the cereal crop density, similar to the system of “wide rows” which is sometimes applied to increase protein content in organic farming (Neumann *et al.*, 2006). In that study, the cultivation of winter wheat with a wide row spacing (48 cm and

36 cm) resulted in higher grain crude protein (0.8 % and 0.6 % higher, respectively) compared with the common row distance (12 cm). Similarly, Hiltbrunner *et al.* (2005) showed that grain protein of winter wheat increased from 11.7 % to 12.7 %, and the TKW increased from 42.6 g to 43.5 g by a wider row spacing (37.50 cm) compared to the narrow row spacing (18.75 cm). Different spatial arrangements can affect crop yield components, such as ear numbers, kernels per ear, and the TKW (Marshall and Ohm, 1987). In the current study, both cereals and lentils obtained a higher TKW at lower proportion (25%). As intra-specific competition among the cereal species may have decreased along with an increasing ratio of the companion crop, they compensated a lower density of heads to a certain extent by a higher TKW. However, the final grain yield of each crop in the study generally decreased as their proportion decreased (submitted to the journal Organic Agriculture).

Unlike cereal crops, lentil grain crude protein content did not vary significantly with the proportion changed in the current study. Generally, legume protein content may differ due to genetic factors, environmental and agronomic conditions and their interactions (Monti and Grillo, 1983). Probably, lentils with their continuously symbiotic nitrogen fixation which are different with cereals stabled the nitrogen supply and demand of the plants and thus steady grain protein content in the study. Additionally, may be there are other lentil varieties which are more sensitive to crop density in total protein content, or also in the protein composition, which was not part of this study.

The differences in the absolute seed crude protein content of crops between years is probably a result of different water supply and temperature in 2009 and 2010; high temperatures during grain filling are usually favorable to increase the grain crude protein of wheat (Rao *et al.*, 1993), particularly in combination with drought (Altenbach *et al.*, 2003).

The combination of the grain legume lentils with cereals (wheat or barley) resulted in a higher total crude protein yield of the whole system, compared with the monoculture of each crop. In countries with lack of protein supply in the food, mixed cropping can be therefore well used to increase the total protein supply for food. However, the effects of mixed cropping on protein quality and the composition of the essential amino acids are still not yet known. Malting barley does not seem a suitable companion crop for lentils from the point of a good malting and beer making process as there is the risk of crude protein levels which may exceed the limits. Wheat quality, on the other hand, may highly profit from mixed cropping with lentil, and maybe with other legumes because of increased protein contents. This system can be recommended particularly for organic farming where high protein contents are not easily to be achieved.

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6 General Discussion

In this dissertation, the main four chapters (2, 3, 4 and 5) are related and each chapter can be read independently with separate discussions at its end. Thus, here the general discussion will provide overall and brief statements on the outcome of the research described in the dissertation, and how these match the objectives of the study outlined in the general introduction part.

The crop ‘lentil’ is grown in many countries worldwide for its’ widely adaptation to agroecological zones. Different cropping systems such as monocropping, double cropping, mixed or intercropping and relay cropping can be chosen for different lentil production regions, depending on the annual rainfall and distribution, the demand of the local cropping cycle, and other factors. Nowadays, lentil monoculture is still a common practice in some regions of India, West Asia and North Africa in where the precipitation is insufficient or the soil is heavy textured (Ali *et al.*, 2009). However, as mentioned before, this sole cropping is somewhat risky due to the unstable crop performance and yield achievement over years, low returns and the buildup of diseases and pests (Sekhon *et al.*, 2007). In Central Europe, where the climate is temperate, choosing lentil mixed cropping or intercropping can be a well option under local conditions. Results from the current study clearly showed the advantages of lentil-based mixed cropping in total productivity (grain yield, LER), seed quality (grain protein content) and weed suppression (weed biomass).

To explore a cropping system which can obtain the maximum crop grain yield and high grain quality adapted to the local conditions is always the important objective. The cropping system can be influenced by genetic factors of crops, the environmental and agronomic factors, or their interactions. Thus, to improve and optimize a lentil-based mixed cropping system should be focused on these key aspects.

Companion Crop Species and Mixing Ratios

Choosing suitable lentil genotypes and companion crop species are both important issues for a lentil mixed cropping system. Tanwar (2003) pointed out that selecting the crop is an essential management decision because it specified the environmental requirements such as for water demand, crop growth duration and the compatibility such as in crop rotations. In the current study, only one lentil genotype 'Anicia' was tested in lentil mixed cropping with five companion crops (barley, wheat, oat, linseed and buckwheat). There may be other genotypes which can show similar or better performance if mix-cropped with these companion crops. For example, the genotype 'Berglinse' which was tested in a standard lentil-barley mixed cropping system (Chapter 3) could be considered as an alternative.

In lentil-cereal (wheat and barley) cropping systems in this study (Chapter 2), a higher land equivalent ratio (LER) nearly 1.50 was obtained, which demonstrated the superiority of yield potential of mixed cropping compared to monocropping reflected in land use efficiency. Although the LER values in the study were over-estimated due to the lower seeding density in companion crop sole cropping (240 seeds m^{-2}) compared with practical farming (e.g. ca. 400 seeds m^{-2} in wheat monoculture), lentil mixed cropping was still promising. This was in line with some previous studies on lentil-cereal mixed or intercropping (Ciftci and Ülker, 2005; Yağmur and Kaydan, 2006; Wahla *et al.*, 2009). Cereals are the common crop suitable for growing with legumes because of their relatively higher growth rates, greater height and more extensive root systems, which could be favored when associated with legumes (Ofori and Stern, 1987).

The lentil examined in the current study showed that it needs the companion crop's support to resist lodging. Lodging always causes yield loss because seeds close to the ground cannot be picked up by a combine harvester, and also a loss in grain quality because of the risk of higher grain moisture, pre-harvest sprouting and infection with fungi. Especially under wet conditions such as in Central Europe, lodging could occur often. Thus, the choice of a suitable companion crop should consider, besides yield and land equivalent ratio, the potential to prevent lentils from lodging. Results of the study presented in this thesis showed that all tested species except for the linseed can be well used as a companion crop with lentils. Linseed turned out to be especially unsuitable for mixed cropping with lentils due to its slim stem which could easily lodge in the current study. Besides, the fiber in the linseed stems caused serious harvest problems. Similarly, Neupane and Bharati (1993) pointed out that no beneficial effect can be found in lentil-linseed intercropping system in Nepal. Contrarily, Mishra and Ali (2002) reported that lentil-linseed intercropping had better compatibility in

India and the lentil genotype ‘L4076’ got higher grain yield than ‘DPL62’ in this cropping system. Therefore, the performance of companion crop may vary under different locations or climate conditions.

Besides selecting crops, using an optimum seed ratio of the mixture is also important in lentil mixed cropping. Taking lentil-wheat mixed cropping for example; Ciftci and Ülker (2005) reported that 80%:20% or 70%:30% (lentil: wheat) mixing ratios achieved high LER, while Ahmed *et al.* (1987) noted that 2:1 or 1:2 were the most compatible and profitable seeding ratios. In the presented studies, different lentil-based mixed cropping systems with a ratio of 3:1 (lentil: companion crop) showed higher total productivity (LER) and seed quality (grain protein content) than other mixing ratios (1:1 or 1:3). Different proportions in the mixture means different crop densities, which may have effects on intraspecific and interspecific competitions of crops and thus the final grain yield differ. This also depends on companion crop species. Results from the study indicated that the competition capacity of the cereals was high toward lentils in lentil-cereal cropping systems, however, in lentil-linseed and lentil-buckwheat cropping systems, lentil seemed to have similar interspecific competition ability. The competition ability of lentils could also depend on the climate. As shown by Ahlawat *et al.* (1985), lentils mixed cropped with wheat seemed to be more competitive in sub-humid than in semiarid environments.

Sowing Time

Normally, the rainfall during lentil growth period is quite enough in Central Europe due to the temperate climate in this region. Hence the attention was shifted to the optimum sowing time and the effective weed control to further optimize a lentil-based mixed cropping system. Lentil planting time differs according to diverse types of agroecological zones. The time of sowing is always related to plant growth and phonological development and thus the final grain yield (Ali *et al.*, 2009). It was reported that delayed sowing of lentils reduced the incidence of soil-borne pathogens (Singh and Dhingra, 1980); however, it may result in yield reduction (Kumar *et al.*, 2005). Results from Chapter 3 showed that both lentil and barley grain yields were generally reduced if the sowing time was delayed in a traditional lentil-barley mixed cropping system. The maximum yield reduction could be more than 50%

for both crops. As lentils are usually quantitative long-day plants, they have a quantitative response to photoperiod and flower more quickly during longer days compared to shorter days (Summerfield and Roberts, 1988). If sowing earlier (end of March or beginning of April), it will allow a longer period for crop vegetative and reproductive growth and thus more accumulation of dry matter compared to late sowing, especially under comparatively short-day conditions in spring in Central Europe, resulting in potentially higher grain yields. Results of this study agreed with the studies (Silim *et al.*, 1991; Siddique *et al.*, 1998) which indicated that lentil seed yields declined with delayed sowing in dryland Mediterranean-type environments of south-western Australia, and in northern Syria. In addition, in the study, early sown lentil/barley mixture suppressed emerging weeds efficiently than late sown mixture generally, probably due to the higher total biomass production of the crops and increased tillering of the barley, resulting in higher competiveness of the total mixture. This weed suppressing effect may vary if companion crops are different in lentil-based mixed cropping systems. However, in an optimal lentil-companion crop mixed cropping system, early sowing can be an appropriate method to indirectly control weeds. Especially for lentils, the crop which has low competitive capacity against weeds. On organic farms, cultural practices and mechanical control can be used to prevent weed infestation. However, mechanical weed control is always difficult for lentils because of damage to the lentil shoots and roots attributed to the sensitivity (Stringi *et al.*, 1988) and twining architecture (Muehlbauer *et al.*, 1985) of the crop. Thus, alternative methods such as woodchips mulching can be adopted in a lentil-based mixed cropping system, which suppressed weeds more effectively. This will be generally discussed in the following section of the thesis.

Weed Control

It is well-known that weeds are one of the most important agronomic problems especially on organic farms. Farmers always need energy- and time-consuming efforts to control weeds. Especially lentils have less competition ability against weeds in the early vegetative stage of plant development (Muehlbauer *et al.*, 1981). In Chapter 2 and Chapter 4 was demonstrated that weed suppressing effect was generally enhanced by lentil-based mixed cropping compared to lentil monocropping, particularly in combination with woodchips mulch. Weed biomass could be reduced by 24-41% along with mixing ratios (3:1, 1:1, and 1:3) in different mixed cropping systems; if applying woodchips mulch combined with mixed cropping, the percentage of weed biomass reduction could reach 51% (lentil-barley mixed cropping). One important reason could be the reduced light availability for weeds under a crop canopy of lentil mixed with highly competitive cereals (higher LAI of the mixtures). Mulching with woodchips covers the soil and thus may prevent weeds from germination and/or emergence. Besides this, probably the below-ground competition of crops against weeds in use of resources (e.g. water and nutrients) may also be improved in mixed cropping systems especially together with woodchips mulch applying. Some studies (Hauggaard-Nielsen *et al.*, 2001; Liebman and Dyck, 1993; Olasantan *et al.*, 1994) also considered crop mixed cropping can be very efficient in terms of weed control. The weed infestation was significantly lower in mixed cropping than in monocropping in other legume-cereal mixed or intercropping systems (Agegnehu *et al.*, 2006; Banik *et al.*, 2006). All of these suggested that mixed cropping can be a practical method for weed management in organic lentil production. Particularly, the combination of woodchip mulch and mixed cropping is useful to reduce weed infestation in cropping systems where chemical or mechanical weed control is not possible and for crops with a low capacity for competition against weeds.

Seed Protein Content

In the study, mixed cropping of lentils with cereals can be well used to increase the total protein supply for food compared with lentil or cereal monoculture, which is important especially in countries with lack of protein supply. Meanwhile the food diversity can be improved as well. Besides, the cereal crop quality gets profit from mixed cropping with lentils. A higher crude protein content of cereals (wheat or barley) could be achieved when the proportion of the cereals in the mixture with lentils was low (e.g. 25%) in the study (Chapter 5). The results agreed with some similar studies in legume-cereal mixed cropping systems (Hof *et al.*, 2006; Azizi *et al.*, 2011; Pflaum *et al.*, 2011). Generally, high-quality of cereal grains with high crude protein content is expected, for example for breadmaking (wheat) or for feeding (barley). However, lower protein content is wanted in malting barley for beer making. Thus, this research provides basic information for farmers choosing the proper cropping system. The lentil-cereal mixed cropping can be recommended for high quality of breadmaking, particularly on organic farms where high protein content are not easily to be achieved. Cereal (barley) monocropping seems a better option than mixed cropping for making beer in regard of the lower grain protein content. Up to now, the effects of mixed cropping on protein quality and the composition of the essential amino acids are still not yet known in this study, and this may be the further research aspects in future.

Future Perspectives

In the past, lentil was misunderstood to be grown only in poor land. Our study revealed that "good" sites are also suitable for lentil cultivation, so that many locations can be considered for lentil growing. This means that many organic farmers have an option for to integrate lentils in their crop rotation or mixed cropping system taking advantage of the beneficial effects of crop biodiversity and N-fixation. Thus more lentil growers and increasing acreages under temperate climate conditions in Germany can be expected in future.

Although lentil-based mixed cropping is a promising cropping system, crop harvesting and seed cleaning is another an important issue – which should be considered as it can affect the success of the cropping system to be adopted or not by farmers. Unlike intercropping, mixed cropping usually does not have definite sowing pattern (e.g. strip intercropping). In the current study, lentil and companion crops were sown not in separate lines by using a sowing machine (drill). Thus, lentils together with the companion crop have to be harvested simultaneously by hand pulling (not in industrial countries) or by machine. This requires choosing the suitable companion crops which can fulfill their whole growth cycle with lentil crop almost at the same time. On the other hand, seed separation and cleaning is another big task and time-consuming work in lentil mixed cropping system. Seeds can be separated based on differences in length, width, thickness, weight, shape, surface texture and color (Boyd *et al.*, 1975). However, it is always difficult to separate both crops from each other in some lentil mixed cropping systems due to the similar grain mass and shape. Moreover, lentil seed is susceptible to mechanical damage during the process of cleaning and handling, therefore, the smallest necessary number of machines the better (Bishaw *et al.*, 2007). New mechanical technologies to improve crop harvesting, seed cleaning and processing are required for different lentil-based mixed cropping systems in modern agriculture.

Some studies (Fruwirth, 1936; Kusmenoglu and Aydin, 1995; Hamdi *et al.*, 1996) described the winter hardiness on lentils, and this crop could be considered more tolerant of low temperature than some other temperate grain legumes such as pea (Murray *et al.*, 1988). Therefore, using cold-tolerant cultivars of lentil to reduce the risk of low temperature damage in Central Europe could be expected. Breeding for winter hardiness of lentils for temperate conditions to extend the growth period and further increase yield can be the next step in the story of re-introducing lentils into German organic farming.

7 Summary

As a kind of legume crop, lentils (*Lens culinaris* Medik.) with their high nutritional value are grown mainly for human consumption in many regions of the world. The crop has benefits in crop rotation due to its symbiotic N-fixation, which is important especially in organic farming, and it can also increase crop biodiversity in arable land. In Europe, lentils are considered one of the popular leguminous food crops. However, the cultivation and scientific research on lentils were neglected in Germany and Central Europe over the past 50 years. Recently, farmers have begun to realize the value of lentils and have re-introduced the crop into organic and conventional farming in Central Europe. The lentil plant has a weak stalk and is easily lodging. Lodging plants cannot be completely cut and picked up by combine harvesters, and result in yield loss, especially under the wet conditions that often occur in Central Europe. To avoid lodging of crop, lentils were commonly grown in mixed cropping with cereals, such as oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.) and rye (*Secale cereale* L.). However, there is little current information on lentil cultivation under temperate climates in this region. One of the most relevant challenges for growing lentil is how to explore its yield potential adapt to the local conditions. Moreover, lentil plant has a low competition capacity against weeds which are always one of the big agronomic problems especially on organic farm.

Therefore, three field experiments presented in this dissertation were carried out to design and improve lentil cropping systems under organic farming in Germany in terms of productivity and competitiveness performance, suitable species and proportion of companion crops, lentil cultivars, sowing dates, weed control, and seed quality. The results should be used to adapt lentil cropping systems to different local climatic conditions in Germany. The specific objectives were (i) to optimize lentil-based mixed cropping systems through different combinations of companion crops (barley, wheat (*Triticum aestivum* L.), oat, linseed (*Linum usitatissimum* L.) and buckwheat (*Fagopyrum esculentum* Moench)) and mixing ratios, which were expected to show different performance on crop productivity, weed infestation, and lentil lodging, (ii) to determine whether different sowing time (early, medium, late) have effects on a standard lentil-barley mixed cropping system in regard to crop yield and weed

control, (iii) to test whether woodchip mulch can help suppressing weeds and increasing crop yield in lentil monocropping and mixed cropping, (iv) to determine whether different mixing ratios affect seed protein content in lentil-cereals (barley, wheat) mixed cropping system.

To achieve the first objective, a two-year field experiment of mixed cropping of lentils with five spring-sown companion crops: naked-barley, wheat, oats, linseed and buckwheat was conducted at the organic research station Kleinhohenheim in 2009 and 2010. Besides sole lentil and sole companion crops, three mixing ratios (3:1, 1:1, 1:3) were used. Lentil grain yield was 1.47 t ha^{-1} in monocropping and 0.58-1.07 t ha^{-1} in mixed cropping, depending on the mixing ratio and companion crop (Chapter 2). The land equivalent ratio (LER) was higher in mixed cropping than in monocropping generally. Lentil-wheat and lentil-barley mixed cropping with a ratio of 3:1 resulted in the highest LER (ca. 1.50) whereas lentil-linseed had the lowest LER in all ratios. Lowest lodging was observed in lentil-wheat and lentil-oat mixed cropping. Additionally, mixed cropping with ratios of 3:1, 1:1 and 1:3 (lentil: companion crop) reduced weed biomass by 29%, 41% and 24%, respectively, compared with lentil monocropping. The results indicated that lentil mixed cropping in the study seemed more promising than monocropping under the given conditions of the location. Except for the linseed, all tested species can be well used as companion crops especially the two cereals (barley and wheat) which can be recommended. The mixing ratio should consider the total yield advantage (LER), the risk of crop lodging, and marketing considerations of both crops.

To achieve the second objective of the study, another two-year (2009-2010) field trial was carried out at two sites: the organic research station Kleinhohenheim (KH) and the conventional research station Oberer Lindenhof (OLI) (Chapter 3). The crop was sown at three dates (early, medium and late) in the period from March to May. Four genotypes of lentil: Anicia, Schwarze Linse, Hellerlinse and Berglinse were mixed-cropped with naked-barley at a ratio of 3:1 (lentil:barley) at each sowing date. Results showed that grain yield of crops was significantly higher at the earliest sowing both for lentils (3.0 t ha^{-1} at KH, 2.4 t ha^{-1} at OLI) and barley (1.2 t ha^{-1} at KH, 2.6 t ha^{-1} at OLI). Lentil seed per plant, barley seed per ear, and thousand kernel weight of crops decreased significantly with delayed sowing. At KH experimental site, weed biomass increased significantly with delayed sowing and was independent of the lentil genotype, whereas sowing date had no significant effect on overall weed biomass production at OLI. The results indicated that early sowing can increase the yield of lentils, and can also be used as an indirect method of weed control in organic farming.

To further control weeds to achieve the third objective, a field experiment of applying woodchips mulch on lentils was carried out at the organic research station Kleinhohenheim, in the years 2009 and 2010 (Chapter 4). Two years on average, an amount of 160 m^3 ha^{-1} (fresh matter) woodchips mulch reduced weed biomass and weed density in both cropping systems compared to no mulch treatment, with a reduction by 43% and 29% (sole), and by 51% and 30% (mixed) respectively. Mixed cropping of lentils with barley (3:1) also decreased weed biomass compared with lentil sole cropping; however, no effect on weed density was observed. Lentil grain yield from sole and mixed cropping was 3.0-3.4 t ha^{-1} and 2.1-2.2 t ha^{-1} (2009), and 1.0-1.1 t ha^{-1} and 0.8-0.9 t ha^{-1} (2010). Barley grain yield was 1.4 t ha^{-1} in 2009 and 0.7 t ha^{-1} in 2010. Despite decreasing weeds, the mulch did not improve crops grain yields in mixed or sole cropping. The combination of woodchip mulch and mixed cropping is useful to reduce weed infestation in cropping systems where chemical or mechanical weed control is not possible and for crops with a low capacity for competition against weeds.

Another focus of the study was on seed quality (protein content), especially for cereals (Chapter 5). The two mixed cropping systems: lentil-wheat and lentil-barley with five seeding ratios (4:0, 3:1, 1:1, 1:3, 0:4) were tested at the organic research station Kleinhohenheim in 2009 and 2010 (originated from the experiment 1). Results showed that cereal grain protein increased significantly when their proportion was reduced in the mixture with lentils. Wheat crude protein increased from 10.3 % (2009) and 11.0 % (2010) in monocropping to 11.5 % (2009) and 15.1 % (2010) in mixed cropping with 75 % lentils. Barley crude protein increased in the same way from 13.7 % in monocropping to 15.8 % in mixed cropping with 75 % lentils. However, lentil protein content did not differ significantly across all mixing ratios. Total crude protein in a mixture was significantly higher than that in cereals or lentils monocropping. Mixed cropping with lentils can thus be an option to obtain a high protein content of wheat which is important for a suitable breadmaking quality, particularly in organic farming.

Summarizing, the overall results of the study will open new options for growing lentils in Central Europe from where the crop has vanished over the last decades and may guide the future of lentil production in multi-cropping.

8 Zusammenfassung

Linsen *(Lens culinaris* Medik.), die zu den Leguminosen zählen, werden vor allem wegen ihres hohen Nährwerts zur menschlichen Ernährung angebaut. Aufgrund ihrer Fähigkeit zur Stickstoff-Fixierung sind Linsen interessante Fruchtfolgeglieder, speziell im Ökologischen Landbau. Obwohl sie in Europa zu den wichtigen Leguminosen zählen, wurde die Forschung zu Linsen über Jahrzehnte vernachlässigt. In den letzten 50 Jahren ist diese Kultur beinahe vollständig aus Mitteleuropa verschwunden. In letzter Zeit haben Landwirte wieder begonnen, den Wert der Linse zu erkennen und sie wieder verstärkt im konventionellen und ökologischen Anbau einzusetzen. Da die Pflanzen einen schwachen Stängel haben, neigen sie zum Lagern. Dies hat den Nachteil, dass diese Partien nicht vollständig mit mechanischen Ernteverfahren erfasst werden können und Ertragseinbußen nach sich ziehen. Vor allem bei feuchter Witterung, wie sie in Mitteleuropa herrscht, ist diese Gefahr gegeben. Um der Lagerneigung der Linsen zu begegnen, wurden sie früher gewöhnlich im Mischanbau kultiviert. Typische Mischungspartner waren Hafer (*Avena sativa* L.), Gerste (*Hordeum vulgare* L.) und Roggen (*Secale cereale* L.). Derzeit jedoch gibt es nur wenige wissenschaftliche Untersuchungen zu Stützfrüchten, deren Mischungsverhältnisse im Gemenge mit Linsen, zum optimalen Saatzeitpunkt und zur effektiven Unkrautbekämpfung. Einer der wichtigsten Punkte in der Linsenforschung ist es, dass Ertragspotential zu bestimmen und in den unterschiedlichen Regionen auszuschöpfen. Ein weiterer wichtiger Aspekt ist die Entwicklung von Anbaustrategien zur Vermeidung von Verlusten durch Verunkrautung aufgrund der geringen Konkurrenzkraft der Linsen gegenüber Unkräutern.

Demzufolge wurden im Rahmen dieser Dissertation drei Feldversuche angelegt um Linsenanbausysteme unter ökologischen und konventionellen Anbaubedingungen in Deutschland im Hinblick auf Produktivität und Konkurrenzfähigkeit, geeignete Sorten und den Anteil der Mischungspartner, Saatzeitpunkt, Unkrautbekämpfung und Saatgutqualität zu entwickeln und zu verbessern. Die Ergebnisse der Arbeit sollen dazu beitragen den Linsenanbau an verschiedene lokalspezifische Klimabedingungen Deutschlands anzupassen. Ziele dieser Arbeiten waren: (i) Linsenbasierte Mischanbauverfahren zu optimieren, indem verschiedene Mischungspartner und Mischungsverhältnisse im Hinblick auf Ertrag, Verunkrautung, Lageranfälligkeit und Ertragsqualität (besonders der Rohproteingehalt der Getreidepartner) untersucht wurden, (ii) verschiedene Saatzeitpunkte (früh, mittel, spät) im Gersten-Linsen-Mischanbau im Hinblick auf Ertrag und Unkrautunterdrückung zu testen, sowie (iii) den unkrautunterdrückenden Effekt von Holzschnitzeln im Rein- und Mischanbau von Linsen zu untersuchen.

Zur Bearbeitung der ersten Versuchsfragestellung wurde ein zweijähriger Feldversuch an der Versuchsstation für ökologischen Landbau Kleinhohenheim (KH) (2009 und 2010) angelegt. Dabei wurden Linsen im Mischanbau mit 5 verschiedenen Mischungspartnern (Gerste, Weizen, Hafer, Lein, und Buchweizen) untersucht. Neben dem alleinigen Anbau von Linsen und der fünf Mischungspartner wurden 3 unterschiedliche Mischungsverhältnisse (3:1, 1:1, 1:3) geprüft. Der Linsenkornertrag lag im Monocropping bei 1,47 t ha^{-1} und im Mischanbau, in Abhängigkeit vom Mischungsverhältnis und Mischungspartner zwischen 0,58 und 1,07 t ha^{-1} (Kapitel 2). Der LER war generell im Mischanbau höher als bei Monocropping. Die „land equivalent ratio“ (LER) ist ein wichtiges Maß für die Beurteilung von Mischkulturen. Der Linsen-Weizen und Linsen-Gerste Mischanbau mit einem Mischungsverhältnis von 3:1 erreichte die höchste LER (ca. 1,5), wohingegen der Linsen-Lein Mischanbau in allen Mischungsverhältnissen die geringste LER zeigte. Die geringste Lagerneigung wurde im Linsen-Weizen und Linsen-Hafer Mischanbau festgestellt. Zusätzlich reduzierte der Mischanbau den Unkrautdruck um 29 % (3:1), 41 % (1:1) und 24 % (1:3) gegenüber dem Monokulturanbau. Die Ergebnisse zeigten, dass sich der Mischanbau von Linsen vorteilhafter gegenüber dem Reinbestand unter den gegebenen Standortverhältnissen darstellt. Außer Lein (*Linum usitatissimum* L.) erschienen alle geprüften Mischungspartner (Weizen (*Triticum aestivum* L.), Gerste, Hafer und Buchweizen (*Fagopyrum esculentum* Moench) für den Mischanbau mit Linsen geeignet.

Um der zweiten Versuchsfragestellung nachzugehen wurde ein weiterer zweijähriger Feldversuch (2009-2010) an den Standorten Kleinhohenheim (KH) und Oberer Lindenhof (OLI, konventioneller Landbau) angelegt (Kapitel 3). Drei Saatzeitpunkte zwischen März und Mai wurden an den zwei Versuchsstandorten untersucht. Darüber hinaus wurden vier Linsengeotypen (Anicia, Schwarze Linse, Hellerlinse und Berglinse) im Mischanbau mit Braugerste im Verhältnis 3:1 getestet. Der Linsen- (3,0 t ha^{-1} in KH, 2,4 t ha^{-1} am OLI) und der Gerstenertrag (1,2 t ha^{-1} in KH, 2,6 t ha^{-1} am OLI) waren in der früh gesäten Variante signifikant höher als in den Varianten mit späteren Saatzeitpunkten. Die Anzahl Linsen/Pflanze bzw. Körner/Ähre (bei Gerste) und die Tausendkornmasse verringerten sich signifikant mit späteren Aussatzeitpunkten. Der Unkrautbesatz war durch die späteren Aussaatzeitpunkte in Kleinhohenheim signifikant erhöht, unabhängig von der Linsensorte, wogegen der Saatzeitpunkt keinen signifikanten Effekt auf den Unkrautbesatz am Versuchsstandort OLI hatte. Die Ergebnisse deuten darauf hin, dass frühe Saatzeitpunkte eine indirekte Methode zur Reduzierung des Unkrautdruckes im Ökologischen Landbau darstellen können, und dass eine frühe Aussaat ertragssteigernd wirkt.

Eine weiterhin untersuchte Methode zur Unkrautbekämpfung war die Anwendung von Holzschnitzeln als Mulchmaterialien mit einer Menge von 160 m^3 ha^{-1} auf der Versuchsstation Kleinhohenheim in den Jahren 2009 und 2010 (Kapitel 4). Dies führte zur Reduktion von Unkrautmasse und Unkrautdichte im Vergleich zur Kontrolle von 43 % und 29 % in der Reinkultur und einer Reduktion um 51 % und 30 % im Mischanbau. Der Gerste-Linsen-Mischanbau (3:1) reduzierte die Unkrautmasse ebenfalls signifikant im Vergleich zur Reinkultur, jedoch war kein Effekt im Hinblick auf die Unkrautdichte messbar. Die Linsenerträge der Rein- und Mischkultur lagen bei 3,0 - 3,4 t ha^{-1} und 2,1 - 2,2 t ha^{-1} (2009) bzw. bei 1,0 - 1,1 t ha^{-1} und 0,8 – 0,9 t ha^{-1} (2010). Die Gerste erreichte Erträge von 1,4 t ha^{-1} (2009) und 0,7 t ha^{-1} (2010). Somit konnten trotz der unkrautunterdrückenden Wirkung keine ertragssteigernden Effekte der Holzschnitzel festgestellt werden. Zusammenfassend kann festgehalten werden, dass der Einsatz von Holzschnitzeln als Mulchmaterial und Mischanbau geeignete Methoden sind um den Unkrautdruck zu reduzieren, insbesondere dort, wo chemischer und mechanischer Pflanzenschutz nicht möglich sind.

Ein weiteres Ziel der Arbeit war die Untersuchung des Einflusses verschiedener Mischungsverhältnisse auf den Rohproteingehalt der Mischungspartner Gerste und Weizen. Hierzu wurden aus dem in Kapitel 2 beschriebenen Versuch zwei Mischanbausysteme (Linsen-Weizen und Linsen-Gerste) ausgewählt und die jeweils fünf Mischungsverhältnisse (4:0, 3:1, 1:1, 1:3, 0:4) im Hinblick auf den Rohproteingehalt bewertet. Die Ergebnisse zeigten, dass der Rohproteingehalt des Getreides in beiden Mischanbausystemen mit zunehmendem Linsenanteil im Mischungsverhältnis signifikant anstieg. Der Rohproteingehalt des Weizens im Mischanbau mit 75 % Linsenanteil (11,5 % in 2009 und 15,1 % in 2010) konnte im Vergleich zur Reinkultur (10,3 % in 2009 und 11,0 % in 2010) gesteigert werden. Gleichermaßen stieg der Rohproteingehalt der Gerste von 13,7 % in der Reinkultur auf 15,8 % in der Mischkultur mit 75 % Linsen. Der Rohproteingehalt der Linsen variierte hingegen nicht in Abhängigkeit verschiedener Mischungsverhältnisse. Der gesamte Rohproteingehalt innerhalb eines Mischanbausystems konnte im Vergleich zum Anbau von Getreide bzw. Linsen in Reinkultur signifikant gesteigert werden. Somit bietet der Mischanbau mit Linsen im ökologischen Landbau die Möglichkeit, einen hohen Rohproteingehalt im Weizen, als wichtigen Qualitätsparameter im Hinblick auf die Backeigenschaften, zu erzielen.

Zusammenfassend zeigen die Ergebnisse dieser Arbeit neue Optionen für den Anbau von Linsen in Mitteleuropa auf und können somit dazu beitragen, dieser in ihrer Bedeutung stark zurückgegangenen Kultur sowie dem Mischanbau im Allgemeinen wieder zu verstärktem Einsatz zu verhelfen.

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11 Curriculum Vitae

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